Potential interest areas for the development of geothermal energy in La Reunion Island

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ABSTRACT

La Réunion Island was always considered as a high interest for the geothermal exploitation and several exploration surveys were performed since the 70's. However, at the present day, no geothermal exploitation has been built. Nevertheless, the French environmental law, Grenelle de l'Environnement, has set ambitious goals for the French overseas territories and La Réunion must be self-powered by 2030.

In this framework, BRGM and the Geoscience Laboratory of La Réunion University in collaboration with Région Réunion, LMV of Clermont-Ferrand University and La Réunion National Park, with the financial support of DREAL and ADEME, the French energy agency, have conducted a new exploration project.

This project aims to perform a synthesis of the knowledge of the island and to define the most favourable areas for exploiting geothermal moderate and high temperature resources. This study is based on a bibliographic compilation integrating the previous geothermal exploration surveys from the 70's to the 2000's, the recent results of the La Réunion University studies and the heliborn magnetic and transient electromagnetism (TEM) survey of 2014. All these data were integrated in a Geographic Information System (GIS) in order to provide maps of geothermal interest.

Therefore, three thematic maps have been performed (geology and geochemical data, geophysical data and environmental issues) and a global synthesis map showing the favourable areas for geothermal energy development based on the classical criteria used in volcanic context exploration, and also the criteria of non-conventional geothermal energy as Engineered Geothermal System (EGS):

- High thermal gradient in boreholes
- Hot springs, fumaroles, travertines, gas anomalies;
- Geological discontinuities such as fractures, faults, and magmatic intrusions;
- High electric resistivity layer constituting a reservoir overlaid by a conductive layer that can be a cap rock (model of Johnston *et al.*, 1992).

This synthesis leads to the definition of several geothermal targets, which can be grouped in three sets of interest:

- The proven interest areas;
- The interest areas to be confirmed;
- The interest areas located in protected areas (inside the National Park).

The analysis of the previous surveys shows that if thermal anomalies exist, permeability of the geological formations seems to be poor and insufficient for geothermal exploitation. There is a moderate chance that a classical volcanic system exists at La Réunion Island. Therefore, the next exploration phases should take into account the non-conventional geothermal exploitation, like EGS, which consist in improving the development of the wells for optimizing their productivity in order to reach a sufficient economic return.

1. INTRODUCTION

La Réunion island is a ~5 Myr old basalic edifice with a subcircular shape of 200 × 240 km, built on the oceanic floor at 4000 m below sea level by the Reunion hotspot. The subaerial part of La Réunion is made of two main volcanoes, Piton des Neiges to the West, which is inactive and incised by three cirques (Salazie, Mafate and Cilaos) and Piton de la Fournaise to the East, which is active (Figure 1).

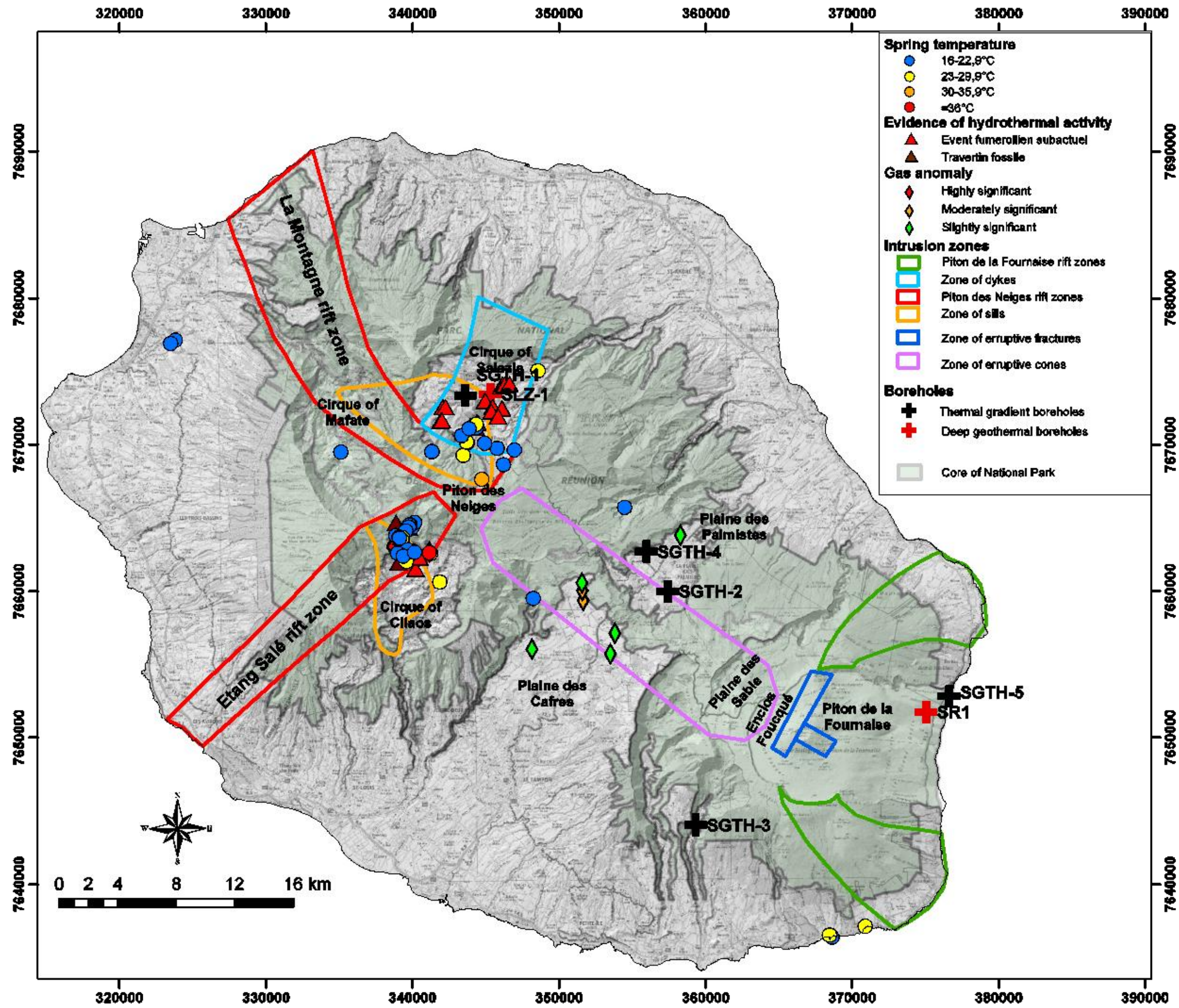

Figure 1: Map of La Réunion Island and geological and geochemical elements take into account in this study.

Due to the presence of these two volcanoes, La Réunion Island is considered as an interesting area for geothermal energy, and several geothermal exploration studies have been performed in the last decades, yet no exploitation project has emerged from these studies.

However, the 2007 "Grenelle Environnement" environmental agreements have set ambitious objectives for overseas territories, and imply long-term decisions in terms of sustainable development. For La Réunion Island, the objective is to achieve energetic independence for 2030. Moreover, the President Nicolas Sarkozy asked to yield mapping of geothermal resources. Following this strong governmental commitment, this study has been done in order to perform a synthesis of the knowledge, in terms of geothermal energy, to define the most appropriate areas for geothermal exploitation (Dezayes *et al.*, 2015). This study includes the most recent subsurface data and researches, and takes into account the environmental constraints imposed by the Nation Park, which constitutes a UNESCO World Heritage Site.

Based on a synthesis of the bibliography, and a short field tour to evaluate the accessibility, the interest of exploitation and the surface evidence of geothermal activity, we built a GIS (Geographical Information System) including all the data having an interest for geothermal energy. Then, three synthetic maps have been made: geology and geochemistry, geophysics and environmental constraints. A global map showing the main analysis and the most favourable areas for conventional geothermal exploitation but also for EGS (Enhanced Geothermal System) summarises all the data.

2. SYNTHESIS OF PREVIOUS WORKS

From the 70's, several exploration campaigns have been performed by different organisations on the Island. These previous exploration works are summarized in table 1.

Exploration Phase (Year)	Surveys Completed	Primary Report
Initial Investigations Geology and water geochemistry (1978)	Volcanological evolution, geochronology. Volcanic heat sources and surface hydrothermal alteration. Geological structure. Inventory of hot springs and geochemistry. Identification of zones of interest. Suggested ongoing exploration (geophysics) program.	Lopoukhine et Stieltjes (1978)
Second Phase Investigations Geology and geophysics (1978 – 1979)	Detailed structural analysis. Detailed volcanology and dating to define heat sources. Sampling and preliminary hydrothermal alteration interpretation. Initial geothermal conceptual model. Gravity, magnetotelluric, and spontaneous polarisation geophysical surveys, interpretation.	Gerard et Stieltjes (1979)
Geothermal Evaluation. Geology, geochemistry, geohydrology, geophysics, and thermal gradient wells. (1981)	Volcanology and litho-stratigraphy. Geothermal implications of geological structure. Surface hydrothermal alteration. Geohydrology and geochemistry of springs. Formation of the cirques. Gravity surveys. MT surveys, low frequencies. Audio magnetotelluric. Schlumberger resistivity. Dipole – dipole resistivity. Spontaneous polarisation. Temperature gradient well drilling. Geothermal synthesis. Recommended exploration drilling.	Gérard *et al.* (1981).
Hydrothermal alteration, Piton des Neiges. (1982)	Detailed hydrothermal alteration studies	Rançon (1982a).
Deep exploration well, Grand Brûlé (SR1). (1985)	Well drilling. Well stratigraphy. Well hydrothermal alteration. Well thermal gradient.	Rançon (1986).
Deep exploration well, Salazie (SLZ1). (1985 – 1986)	Well drilling. Well stratigraphy. Well hydrothermal alteration. Well thermal gradient.	Chovelon (1986).
Assessment of deep exploration drilling. (1986)	Geothermal evaluation. Reinterpretation of geophysics based on well results.	Demange (1986).
Review of Réunion geothermal potential. (2000)	Review, including new data since 1986, and assessment of geothermal potential. Comparison with Hawaii. Potential for "Hot Dry Rock", "Hot Fractured Rock", and "Enhanced Geothermal Systems". Low enthalpy usage. Constraints on development.	Sanjuan *et al.* (2000)
Geochemical Surveys (2001)	Thermal spring survey, Cirques of Salazie and Cilaos. Soil Gas (CO_2, CH_4, O_2, He, Rn) survey.	Sanjuan *et al.* (2001)
Geological structure survey. (2001)	Analysis of dikes, joints and faults along profiles, to define geothermal reservoir permeability.	Sanjuan *et al.* (2001)
Updated conceptual model (2001)	Integration of 2001 geochemistry and geology into a conceptual model.	Sanjuan *et al.* (2001)
MT Survey (2002)	MT, AMT and TDEM survey conducted by Phoenix Geophysics	Phoenix Geophysics (2002) PB Power (2002) PB Power (2003)
MT Survey (2004)	MT and TDEM survey conducted by Geosystem	Geosystem (2004) Geosystem (2005) PB Power (2005)

Table 1: Main geothermal exploration phases in La Réunion Island from PB Power, 2002 completed by recent works.

A first investigation phase has been performed in the 70's in order to inventory surface and subsurface evidence of present and past geothermal activity. In the 80's, five thermal gradient wells and two exploration wells have been drilled (Table 2).

Name	Borehole	Year	Depth (m)	Temperature (°C)
SGTH-1	FORAGE GEOTHERMIE GRADIENT DE ROCHE PLATE - SALAZIE	1980	201	57
SGTH-2	FORAGE DE GRADIENT GEOTHERMIQUE DU PITON DES FEES - PLAINE DES PALMISTES	1980	235,3	19,2
SGTH-3	FORAGE GRAND GALET RIVE DROITE DE LA RIVIERE LANGEVIN	1981	202,9	17,7
SGTH-4	FORAGE DE GRADIENT GEOTHERMIQUE DU REMPART - PLAINE DES PALMISTES	1981	127,2	16,2
SGTH-5	FORAGE GRADIENT GEOTHERMIQUE GRAND BRULE VIERGE PARASOL	1981	235,2	17,4
SR1	FORAGE GEOTHERMIQUE DE GRAND BRULE - PITON DE LA FOURNAISE	1985	3003,5	143,7
SLZ-1	FORAGE GEOTHERMIQUE DE SALAZIE - MARE A VIEILLE PLACE	1986	2108	192

Table 2: Boreholes for geothermal exploration in La Réunion (location on figure 1).

The thermal gradient wells have been drilled in different interesting areas of the Island and reach 125 to 235 m (Table 2, Figure 2). These wells show an almost zero gradient of 200 m, except one well located in the Salazie cirque (SGTH1) which reached 57°C at 201 m depth, or a 180 °C/km gradient. In the following drilling campaign, two deep wells have been drilled, one on Piton de La Fournaise at the Grand-Brûlé (SR1), and one on Piton des Neiges in the cirque of Salazie (SLZ1) (Figure 1).

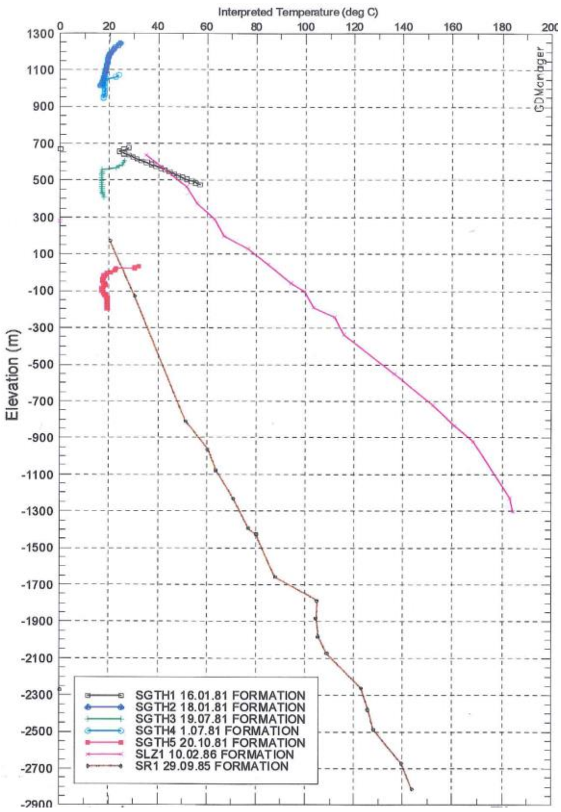

Figure 2 – Temperature gradient in the geothermal wells (in PB Power, 2002).

The first deep well at the Piton de la Fournaise reached a depth of 3003 m with a gradient not exceeding 48 °C/km (Figure 2). The major achievement of this well was to reach a frozen pluton interpreted as the magmatic chamber of a former volcano called “Les Alizées”, which constitutes an important discovery for the geological history of La Réunion Island (Rançon *et al.*, 1987).

The second well at Salazie reached 2108 m depth and a thermal gradient of 82 °C/km (Figure 2) but a low permeability. This low permeability did not allow an economical exploitation of this well despite the very good thermal gradient.

After this phase, geothermal exploration has been abandoned during 15 years. At the beginning of the 2000’s, a review (Sanjuan *et al.*, 2000) and some surveys (Sanjuan *et al.*, 2001; PB Power 2003, 2005) have been performed, ending up with a targeted drill site in La Plaine des Sables on the Piton de la Fournaise. However, this site was included in the UNESCO World Heritage and the well was never drilled in this environmental protect area (Figure 1).

2.1 Geological aspect

The two volcanoes of La Réunion Island have been built by successive lava flows with a dominantly effusive activity, and breccia deposits constituted by the destruction and redeposition of magmatic rocks. In the Salazie cirque, these breccia cover a plutonic complex interpreted as a previous magmatic chamber of the Piton des Neiges (Famin and Michon, 2010,).

All formations are affected by brittle deformation, but especially the older formations in the cirques of Salazie and Cilaos. This brittle deformation essentially consists in faults, for exampletension fractures, and dyke or sill intrusions. Faults and extension fractures are essentially observed in the cirques of Salazie and Cilaos, and to a lesser extent in Mafate. Normal faults are dominant among these deformation structures and are statistically consistent with two perpendicular extension directions, NNW-SSE and WNW-ESE.

The statistical analysis of intrusions distribution and orientation allow the identification of zones of preferential magma injections: On the Piton des Neiges, there are two perpendicular rift zones (Michon *et al.*, 2007, Chaput et al., 2014,). The first one, the La Montagne rift zone, is located in the SW part of Salazie with a N120°E trend and continues to the cirque of Mafate cirque toward Saint Denis with a N160°E trend. The second rift zone, so-called the Etang Salé rift zone, trends toward the N30°E direction ont the SW part of Piton des Neiges. In addition, there are also some zones of sill concentrations, called “sill zones”, in the cirques of Salazie and Cilaos (Chaput et al., 2014). On the Piton de la Fournaise, two main rift zones are observed, a N30°E rift zone on the NE side of the Enclos Foucqué caldera and N150°E one on the SE side (Figure 1).

These preferential directions of tectonics and intrusions are consistent with the directions of the paleo-dorsal and the paleo-transform faults of the oceanic crust, which suggests a regional control of the crust on the tectonics and intrusive activity of La Réunion (Michon *et al.*, 2007, Chaput *et al.*, 2014).

2.2 Hydraulic circulations

The hydraulic circulation within the Island is particularly complex due to the geological context : superimposition of lava flows and breccia with lateral variations. The recent studies show that a continuous hydrogeological model (model “Canarien”, Join *et al.*, 2005) can be applied to the Piton de la Fournaise to explain subsurface circulations. Applied to the Piton des Neiges, this model implies a connection between meteoritic water and deep hydrothermal fluids. This can explain the weak equilibrium temperature (100°C-130°C) computed based on geochemical analyses of the springs of Salazie (Sanjuan *et al.*, 2001). These springs are located at the South of the cirque and are often associated with evidence of hydrothermal activity (Figure 1). Elsewhere, the geothermometers indicate temperatures less than 70°C, except in the Bébour-Bélouve area (Bras Cabot spring, Sanjuan *et al.*, 2000, Figure 1).

Moreover, the permeability of formation decreases with depth and the altered deep formations, like breccia and oceanite lava flows, are plugged by secondary minerals (Folio, 2001).

The circulation of hydrothermal fluids is thus focused along deformation structures and intrusions. This type of circulation is particularly difficult to identify because it requires high spatial resolution techniques of investigations to detect the the pathway of hydrothermal fluids. Perhaps is this why surface, measurements of soil gas did not indicate large fluid leaks, except CO_2, He and Rn anomalies close to Ilet Chicot in the cirque of Cilaos, in Plaine des Palmistes and Plaine des Cafres (Figure 1, Sanjuan *et al.*, 2001).

2.3 Geophysical data

A lot of geophysical data has been acquired on La Réunion Island since the 70’s: gravity, magneto-tellurics, spontaneous potential, heliborn magnetic and transient electromagnetism. All the data are listed and mapped and the quality of the data has been evaluated (Figure 3).

The main resistivity data are MT (Magneto-tellurics), AMT (Audio Magneto-Tellurics) and CSAMT (Controlled Source Audi Magneto-Tellurics) and are stored in different WingLink bases (about 300 data, PB Power, 2005), except the data acquired in 1979 and 1980 (Gérard & Stieltjes, 1979; Gérard and Rançon, 1981) that are not precisely located. However, these data are shallow and are not very interesting for deep exploration. Many issues have been detected in the database, mainly concerning the location with the coordonate transformation. Most of data have been corrected and a quality index (from 1, bad, to 4, good) has been attributed to the data, following the deep interface detected. The areas with the most resistivity data are the Plaine de Sables, with 3D data, and the cirques of Salazie and Cilaos (Figure 3).

Gailler (2010) has compiled all gravimetry data with totally around 2250 measurements and done a Bouguer anomaly map (Gailler & Lénat, 2012).

Spontaneous potentials have been also acquired between 1981 and 2003 in La Plaine des Palmistes, La Plaine des Cafres and the Piton de la Fournaise (Lénat *et al.*, 2003b). About 8000 measurements have been collected and are of good quality.

More recently, a heliborn magnetic and transient electromagnetism (TEM) survey has covered 70% of the island (Martelot *et al.*, 2014). Whereas these data reach only a depth of about 250 m, some of cross-sections have been used to help the analysis of the zones of geothermal interest.

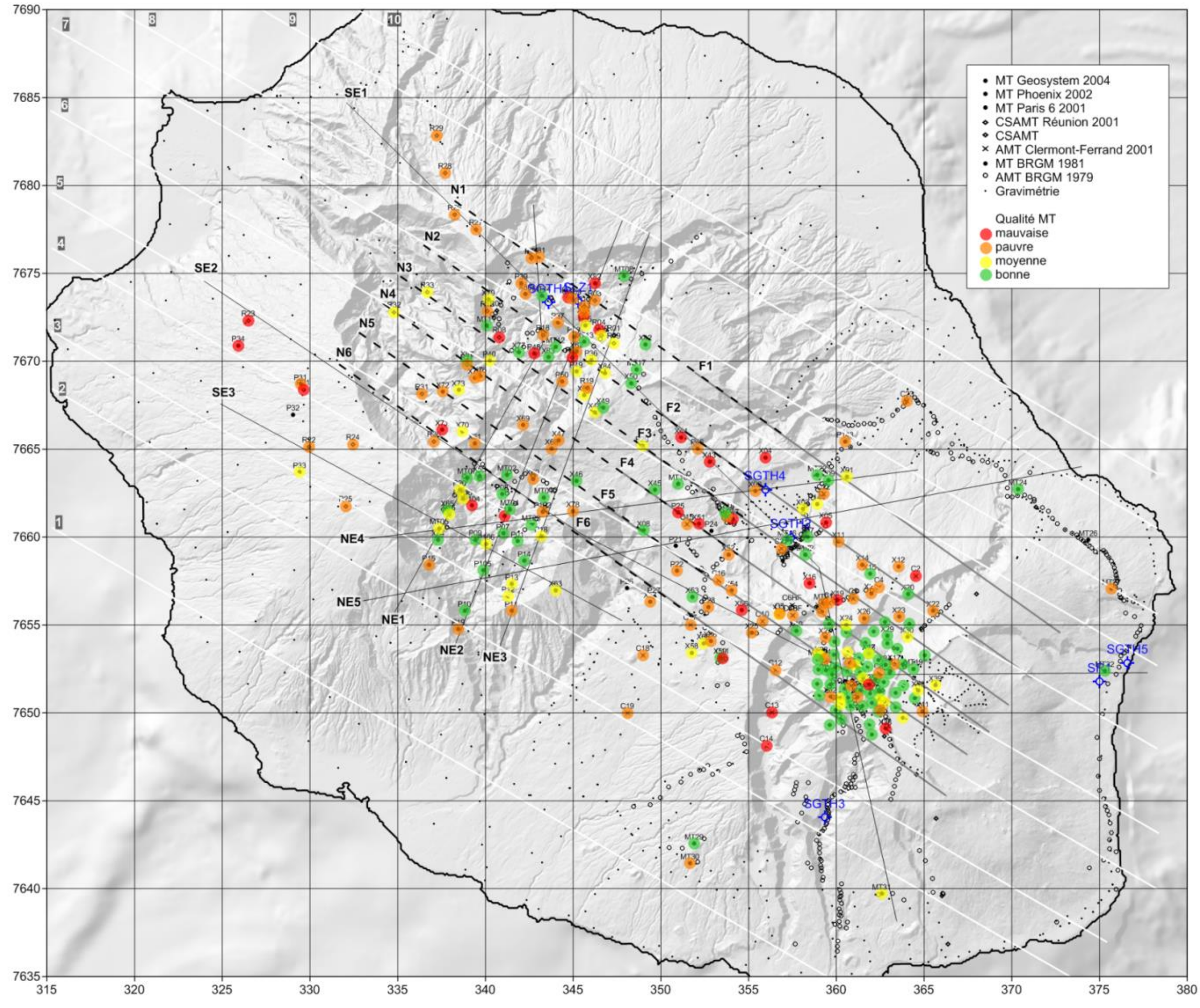

Figure 3: Map of the quality of resistivity data.

3. FAVOURABLE GEOTHERMAL AREAS

3.1 Favourability criteria

All data collected have been included in a GIS in order to identify the most favourable areas for developing medium and high temperature geothermal energy. No previous model has been taking into account in order to exploit all geothermal systems included EGS (Enhanced Geothermal System).

The criteria taken into account to define the geothermal zones of interest are following:

- high thermal gradient identified in the boreholes;

- hot springs, surface evidence of hydrothermal activity, soil gas anomalies showing a hydrothermal flux;

- geological discontinuities like faults, dykes, sills,… to help the transfer of hot fluid to the surface;

- dense bodies at depth which could be an old plutonic complex acting as a heat source;

- high resistivity discontinuities which could constitute a geothermal reservoir with a conductive layer forming a cap rock (model of Johnson *al al.*, 1992).

Based on these five criteria, we determine several zones of interest grouped in three main classes (Table 3, Figure 4).

1- Zones with a high geothermal potential, a lot of data, previous studies and convergent results;

2- Zones whose potential needs to be confirmed, with few but interesting data, and which need more investigations;

3- Zones with a geothermal potential but located inside the National Park.

High potential	Potential to be confirmed	Potential in protected areas
Cirque of Salazie Cirque of Cilaos	Plaine des Cafres Rift zone of Etang Salé Rift zone of Piton de la Fournaise (St Philippe, Ste Rose) Plaine des Palmistes Rivière Langevin - Rivière des Remparts	Plaine des Sables Bébour-Bélouve

Table 3: Areas potentially favourable to developing geothermal energy.

3.2 Description of the geothermal targets

3.2.1 Zones with high interest

Several clues show that the Piton des Neiges constitutes the most favourable area for developing geothermal energy, medium and high temperature.

Cirque of Salazie

The cirque of Salazie has been very studied for geothermal exploration and even for scientific goals. Two boreholes (SGTH and SLZ, Table 2) show a high thermal gradient ≥ 86°C/km, which constitutes three times as much as the thermal gradient of a stable continental crust.

The hot springs in the Mât river are a mix of meteoritic waters and deep waters. The equilibrium temperature computed with geothermometers indicates about 100°C, which shows a relatively superficial hydrothermal system.A gabbro, corresponding to the dense body inferred from gravimetric data, is reached by the deep well SLZ1 and outcrops in the Mât river. This gabbro body is pluri-kilometric and constitutes an old magmatic chamber of the Piton des Neiges. This body is overlaid by basic breccia and basaltic lavas. These formations have weak porosity due to the precipitation of secondary zeolite. However, they are very fractured with a dominant population of normal faults oriented N100°E-N120° and (Chaput et al., 2013). These faults are associated with dyke and sill intrusions.

Analysis of MT, compared to geological formation, shows that it could exist a fossil alteration zone (PB Power, 2002, 2003), but no typical geothermal system as defined by Johnston *et al.* (1992) in volcanic context. A more conductive area is observed to the South of the cirque, confirmed by TEM data, where exit hot springs. This dense and conductive zone could constitute a permeable zone that may favour the rise of hydrothermal fluids.

All these elements converge to the South of the cirque of Salazie, close to the central part of the Piton des Neiges, as a high interest area (Figure 4).

Cirque of Cilaos

The cirque of Cilaos shows the same configuration as Salazie, in its northern part, that is close to the Piton des Neiges.

Several hot springs are present, as thermal baths, and show a 130°C geothermometer. Moreover, a soil gaz anomaly (CO_2, He, Rd) is present to the NW of the cirque, showing fluid circulation.

Many MT data show, as in the cirque of Salazie, a dense structure under a conductive layer (Gailler and Lénat, 2012), but which does not correspond to a typical hydrothermal system.

Therefore, the Cilaos cirque constitutes a high interest zone in the northern part, close to the Piton des Neiges. However, the access conditions are difficult and should be take into account for a drilling project.

3.2.2 Zones with interest to be confirm

These zones could interesting zone by different aspects, but not enough data are available in order to estimate the geothermal potential.

Plaine des Cafres

This area is located between the two volcanoes, close to an urbanised zone.

Several soil gas measurements show an anomaly in one or two of the three measured gas (CO_2, He, Rd).

The MT profiles crosscutting this area show a resistivity signature that could be associated to a classical geothermal system, but this supposed system would be discontinuous and of little extension (PB Power, 2003a). This system needs to be better defined by other geophysical investigations.

Plaine des Palmistes

Two gradient wells have been drilled in La Plaine des Palmistes, near La Plaine des Cafres. These wells show an almost zero gradient. Only one soil gas measurement shows a Radon anomaly.

The MT data do not show a conductive layer, which does no plead in favour of classical a hydrothermal system.

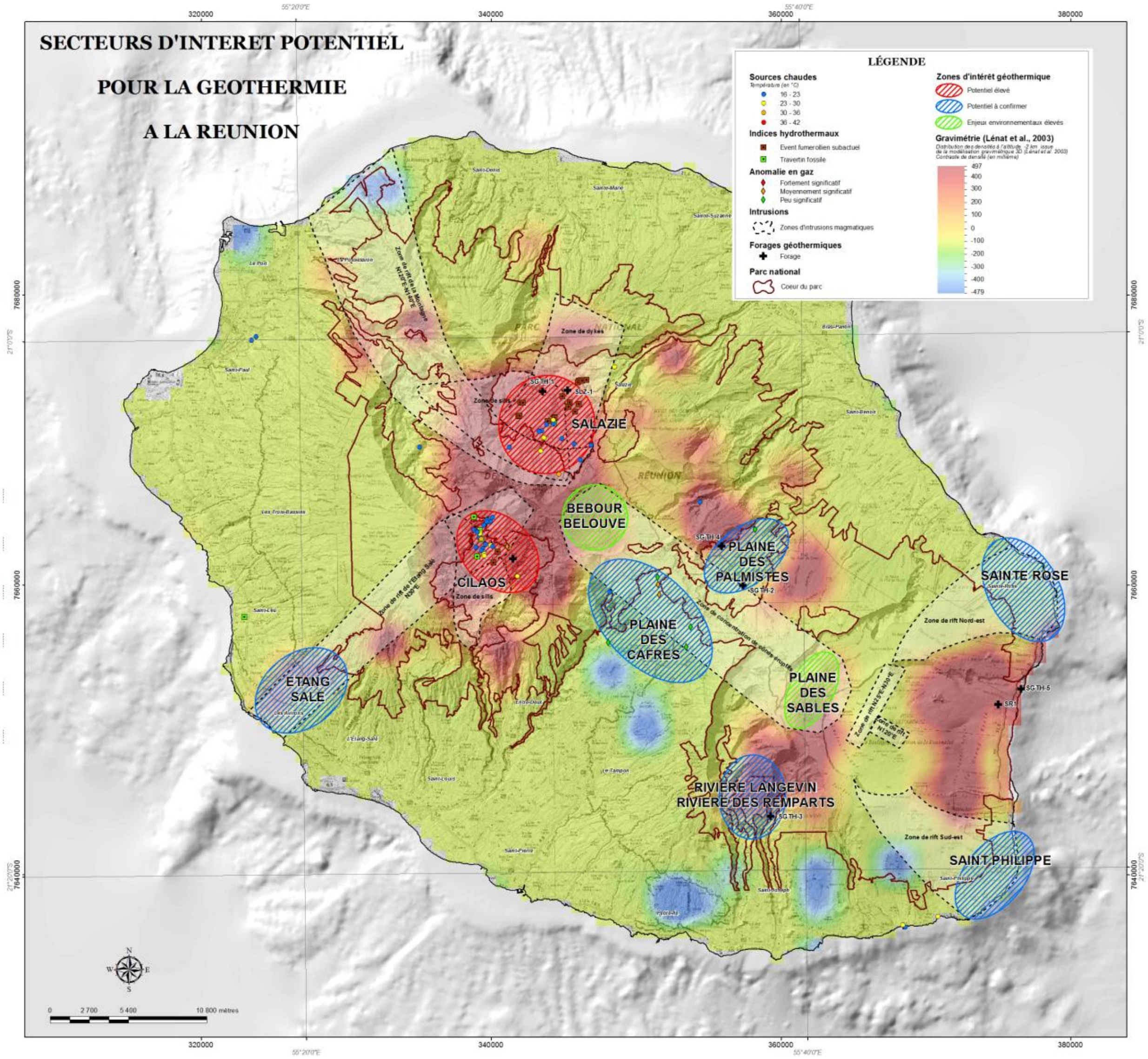

Figure 4: Secteurs d'intérêt potentiel pour la géothermie à l'île de La Réunion.

Etang Salé

The Etang Salé area is the extreme western limit of the rift zone of Etang Salé that trends N30°E from Piton des Neiges to the sea.

This rift zone constitutes a large regional structure, which could affect the oceanic crust and allow the circulation of deep fluids.

The Gravity model (Lénat *et al.*, 2003a, Figure 4) shows high density areas, which could indicate volcanic hypostructures.

Rift zones of Piton de la Fournaise

Two rift zones are presents in the Piton de la Fournaise, which trend N30°E in the NE and N120°E in the SE (Figure 4), as in the Piton des Neiges. However, very few data are available, and include springs with medium temperatures and some geophysical data. The gravity model of (Lénat *et al.*, 2003a) shows a dense body close to this area, which could constitute a heat source. But it is not enough to estimate the geothermal potential.

Rivière Langevin, Rivière des Remparts

Both rivers incise the southern flank of the Piton de la Fournaise, to the South of La Plaine des Sables (Figure 4).

In this area, a gradient well shows a almost zero gradient. Some springs are present but no chemical analysis is available.

From this zone, it has been proposed that a borehole could reach the geothermal system identified by PB Power (2003b) under La Plaine de Sables. However, several kilometers separate the bottom of the valley and the geothermal system. Moreover, the access to these valleys is difficult for large vehicles.

3.2.3 Protected areas with a potential interest

La Plaine des Sables

This area constitutes the NW part of the Piton de la Fournaise and the previous caldera of the volcano (Figure 4).

After the survey performed in the 2000's, La Plaine des Sables has been designated as the most favourable site of the La Réunion Island to drill geothermal boreholes (PB Power, 2003).

A 3D MT survey of very good quality has been performed and a geophysical inversion with different parameters shows that a classical geothermal system exists with a probability of 50% (PB Power, 2005).

A first borehole has been planned to confirm or not the geothermal potential, but due to the location inside the National Park classified UNESCO World Heritage, this project has been cancelled.

Bébour-Bélouve

This zone, at the SE of the Piton des Neiges but outside of the caldera, has some MT data, which show a large space between the conductive layer and the top of the hypostructure, which could indicate the presence of a classical geothermal system. A more detailed survey is necessary to determine the geothermal potential of this area. However, this area is inside the National Park and its access is difficult.

4. CONCLUSIONS

This synthesis of rather 40 years of geothermal investigations in La Réunion Island shows that there is a moderate chance to find a classical geothermal system, as observed in the active volcanic context (Bouillante in Guadeloupe, New Zealand, Johnston *et al.*, 1992).

The future exploration phases should take into account this specificity and explore other criteria, such as discontinuities, and estimate the possibility of enhanced capacity to reach the economical return.

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