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Journal of Volcanology and Geothermal Research 421 (2022) 107450

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

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ARTICLE INFO

Article history:
Received 16 August 2021
Received in revised form 3 December 2021
Accepted 5 December 2021
Available online 09 December 2021

Keywords:
Geothermal resources
Favorability map
Geology
Geophysics
Geochemistry
La Réunion Island

ABSTRACT

La Réunion Island has been considered an attractive target for geothermal exploitation since the 1970s. However, to date, the island's geothermal resources are not being used. Here we use for the first time, a Geographic Information System (GIS) as a decision-making tool to target the most favorable zones for exploitation of moderate and high temperature geothermal resources. All data acquired since the 1970s (geology, geophysics, geochemistry) in addition to environmental constraints such as protection of the National Park that was recently classified as a UNESCO World Heritage Site, were analyzed using the weighted overlay method to delineate favorable areas for local geothermal exploration. Three thematic maps were constructed: geological and structural indicators, thermal indicators, and geophysical indicators. Cross-analysis of these maps highlights two zones that have high geothermal potential; six zones with unconfirmed geothermal potential; and two zones located within the National Park protected area and thus subject to stringent exploitation regulations. It appears that, while thermal anomalies exist in several areas, permeability of the geological formations is low or insufficient for traditional geothermal utilization. Future exploration phases should assess the feasibility of using enhanced geothermal system (EGS) technologies to obtain a satisfactory economic return.

1. Introduction

Overseas territories are off-grid and rely heavily on fossil energy, especially for electricity (Selosse et al., 2018; IRENA, 2019). With the "green deal" in mind, these off-grid territories seek to reach sustainable development in the future. This is particularly the case for volcanic islands that have large geothermal resources that are not highlighted and/or exploited.

The presence of two volcanoes on La Réunion Island, which is located in the Indian Ocean east of Madagascar, makes it a candidate for geothermal energy use and toward this goal, geothermal exploration studies have been conducted in recent decades. Exploration began in the late 1970s with geological and petrological field descriptions, followed in the 1980s by geophysical campaigns and scientific drilling. Additional geochemical and geophysical studies were done between 2000 and 2005. But to date, studies have not led to exploitation, partly because of difficulties in locating high thermal gradient and high fluid circulation zones, and partly due to regulations on plant siting resulting from the creation of the national park in 2007 and classification of La Réunion Island as a UNESCO World Heritage Site in 2010.

Even so, La Réunion Island seeks to achieve energy self-sufficiency by 2030 through the use of geothermal energy. Within this framework, our study aims to locate the most promising geothermal areas based on available geological, geochemical and geophysical knowledge. Our compilation includes all of the exploration surveys to date, plus the most recent volcanological research conducted on the island. Integrating results from different surveys and studies is complex, requires decision-making, and is therefore subject to human error (Noorollahi et al., 2008). For this reason, we use a Geographical Information System (GIS) to help minimize these errors by combining various digital thematic maps that contain geoscientific and environmental data so as to highlight promising areas.

2. Geological setting

La Réunion Island is a ~ 5 Myr old basaltic island, subcircular in shape, with an area of 200 × 240 km, rising from the oceanic floor at a depth of 4000 m below sea level (mbsl), generated by the La Réunion hotspot. The subaerial part of La Réunion Island consists of two main volcanoes: Piton des Neiges to the west, presently inactive and incised by three cirques (Salazie, Mafate and Cilaos) and the active Piton de la Fournaise to the east (Fig. 1). The existence of a third volcano, known

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https://doi.org/10.1016/j.jvolgeores.2021.107450

as "Les Alizés", buried under Piton de la Fournaise, is still under debate (Le Friant et al., 2011; Lebas et al., 2018; Lénat et al., 2012; Lénat et al., 2001; Salvany et al., 2012).

La Réunion Island's two (or three) volcanoes were built up over a succession of construction periods dominated by the effusion of lava flows, and erosional periods, and/or catastrophic flank failures that deposited detrital sediments and breccia. The history of Piton des Neiges has been classified into five eruptive periods separated by erosion (see latest review by Salvany et al., 2012). The first three periods LM (2200–1800 ka), PN1 (1400–950 ka), and PN2 (650–430 ka) correspond to the shield-building stage of the volcano with a dominant emission of mafic, olivine-rich magmas. Two additional periods subdivide the post-shield era: the differentiated stage of Piton des Neiges: PN3 (340–180 ka) with the emission of differentiated, often plagioclase-rich basalts, and PN4 (<140 ka) corresponding to mugearitic to trachytic magmas. Similarly, the construction of Piton de la Fournaise is subdivided into two chrono-stratigraphic sequences separated by landslides or caldera events (Merle et al., 2010). Sequence A corresponds to the emission of plagioclase- and olivine-rich basalts from 550 to 290 ka. Sequence B is composed of basalts with variable olivine contents; it occurred at 220–180 ka. Sequence C, active between 140 and 40 ka, consists of clinopyroxene + olivine ± plagioclase basalts. Sequence D is the last infill of the Plaine des Sables caldera and construction of the modern Piton de la Fournaise; its olivine-rich basalts erupted from 40 to 0 ka. Two major kilometer-scale plutonic complexes of gabbro, wehrlite, and dunite have been identified beneath Piton des Neiges and Piton de la Fournaise. The first plutonic complex crops out in the cirque of Salazie; this complex has been found to extend to 1314 mbsl in the SZ1 drill hole (Fig. 1; Rocher et al., 1987; Demange et al., 1989; Malengreau et al., 1999; Gailler and Lénat, 2012). The

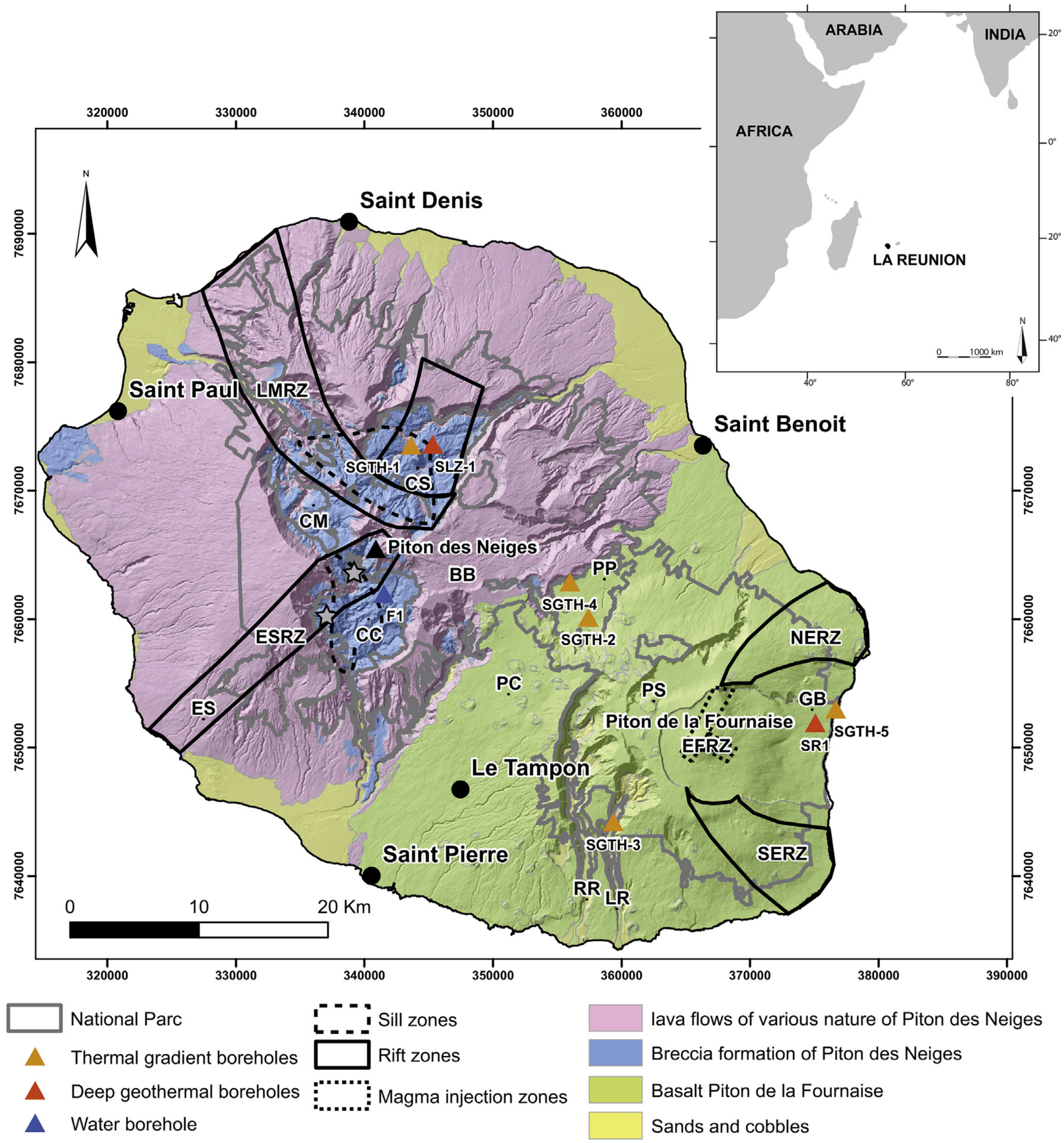

Fig. 1. Simplified map of major geological units of La Réunion Island based on Billard (1974). CS: Cirque of Salazie; CM: Cirque of Mafate; CC: Cirque of Cilaos; BB: Bébour-Bbélouve; PC: Plaine des Cafres; PP: Plaine des Palmistes; PS: Plaine des Sables; GB: Grand Brulé, LR: Langevin River; RR; Rempart River. LMRZ: La Montagne Rift Zone; ESRZ: Etang Salé Rift Zone; EFRZ: Enclos Fouqué Rift Zone; NERZ: North-East Piton de la Fournaise Rift Zone; SERZ: South-East Piton de la Fournaise Rift Zone. Grey stars: Ilet Chicot and Ilet à Cordes, north and west of the Cirque of Cilaos, respectively.

second plutonic complex was identified by geophysics at Grand Brûlé, east of the Piton de la Fournaise summit (Gérard et al., 1980; Rousset et al., 1989); it was encountered in the SR1 drill hole between 828 mbsl and the bottom of the hole at 2831 mbsl (Fig. 1; Rançon et al., 1987, 1989).

All geological units – especially the older formations that crop out in the three cirques – are affected by brittle deformation consisting of faults, extension fractures, and dyke or sill intrusions. Faults and extension fractures are primarily observed in the cirque of Salazie and the cirque of Cilaos, and to a lesser extent in the cirque of Mafate. Normal faults predominate among these deformation structures and are statistically consistent with two perpendicular directions of extension, NNW-SSE and WNW-ESE (Chaput et al., 2017; Chaput et al., 2014; Chevallier and Vatin-Perignon, 1982).

Statistical analyses of adventive cone distribution and of distribution and orientation of intrusions make it possible to identify zones of preferential magma injection, called "rift zones". On Piton des Neiges, two perpendicular rift zones are present (Fig. 1; Michon et al., 2007; Chaput et al., 2017). The first, the La Montagne rift zone, located in the SW part of Salazie, has a N120°E trend; this rift zone continues through the cirque of Mafate toward Saint Denis following a N160°E trend. The second rift, the Etang Salé rift zone, trends in a N30°E direction in the SW part of Piton des Neiges. In addition, zones of sill concentration, called "sill zones", are present in the Salazie and Cilaos cirques (Chaput et al., 2017; Michon et al., 2016; Villeneuve and Bachèlery, 2006). On Piton de la Fournaise, two magma injection trends are observed, an arcuate set of rift zones on the NE and SW sides of the Enclos Fouqué caldera, and a N120°E trend (Fig. 1). These preferential directions of tectonics and intrusions are consistent with the directions of paleo-dorsal and paleo-transform faults of the oceanic crust, suggesting regional crustal control on the tectonics and intrusive activity of La Réunion Island (Chaput et al., 2017; Michon et al., 2007).

The proposed hydrogeological models of Piton de la Fournaise show a continuous basal aquifer of regional extent associated with localized perched aquifers (Canarian type model; Join et al., 2016, 2005). Rock permeability decreases with depth and altered deep formations, such as breccia and oceanite lava flows, are plugged by secondary minerals (Folio, 2001; Nativel, 1978; Rançon, 1985). At a smaller scale, hydraulic circulation within the island can be particularly complex due to the superimposition of lava flows and breccias, intersected by paleo-valleys and magmatic intrusions (Join et al., 2005; Violette et al., 1997). Several thermal springs have been identified and studied on the edifice of Piton des Neiges. These springs are associated with indicators of natural CO_2 and He emanations, of clear magmatic origin (Bénard et al., 2020; Marty et al., 1993) and possible Cl and SO_4 from ongoing degassing of a shallow differentiated magma (Bénard et al., 2020). The major-trace element and Li/Cl isotopic signature of these springs indicate that thermal waters are almost completely disconnected from seawater, which is a noticeable peculiarity for a volcanic island. Their stable isotope signature indicates meteoric origin of these waters (Bénard et al., 2020; Sanjuan et al., 2001). The vast majority of thermal springs are located at the base of the cirques of Salazie and Cilaos, thus are flowing out of old units with low permeability due to prior hydrothermal alteration. However, the springs are often associated with differentiated intrusions (i.e. belonging to the PN3 or PN4 periods), which constitute the most recent activity of Piton des Neiges. Circulation of hydrothermal fluids is thus focused along deformation structures and intrusions. This type of circulation is particularly difficult to locate precisely because it requires high spatial resolution techniques to detect the hydrothermal fluid pathway.

3. Materials and methods

3.1. Previous studies and geothermal exploration history

Various organizations have conducted explorations on the island since the 1970s. In an initial investigation phase (ca. 1970–1980), surface and subsurface indicators of present and past geothermal activity were inventoried (Lopoukhine and Stieltjes, 1978). In the 1980s, five thermal-gradient wells and two exploration wells were drilled to investigate the key parameters at depth: temperature, permeability, and fluid presence (Stieltjes, 1986). Temperature measurement conditions are not documented and no corrections have been applied to them (Table 1). Thermal-gradient wells were drilled in various areas of interest on the island (Fig. 1), reaching depths of 125 to 235 m; the ground temperature of 20 °C has been used to calculate the thermal gradient (Fig. 2). These wells showed an inverted temperature gradient over the first ~200 m, with the exception of one well, located in the cirque of Salazie (SGTH1), that measured 57 °C at a depth of 201 m, i.e. a 184 °C/km gradient.

Two deep wells were drilled after the gradient wells, one in the Piton de La Fournaise area at the Grand-Brûlé (SR1) and the other in the Piton des Neiges area, in the cirque of Salazie (SLZ1, Fig. 1). The SR1 well reached a depth of 3003 m with a gradient not exceeding 48 °C/km and without any major fluid discharge (Fig. 2, Table 1). The major achievement of this well, which was an important discovery for the geological history of La Réunion Island, was to reach the Grand Brûlé pluton, interpreted as a frozen magmatic chamber (Augé et al., 1989; Lerebour et al., 1989; Rançon et al., 1987, 1989). The pluton was later interpreted as related to the Alizés volcano (Lénat et al., 2001). The SLZ1 well, at the cirque of Salazie, reached a depth of 2108 m and, at the bottom of the well, the estimated temperature is 192 °C +/− 8 °C, and no convincing evidence of hydrothermal fluid circulation was found (Demange et al., 1989; PB Power, 2002).

After disappointing drilling campaign, geothermal exploration was abandoned for 15 years. At the beginning of the 2000s, a review (Sanjuan et al., 2000) and new surveys were conducted on Piton des Neiges, in La Plaine des Sables, La Plaine des Palmistes and La Plaine des Cafres (Sanjuan et al., 2001). This work highlighted the presence of relatively superficial hydrothermal systems ($T_{max} = 130 \pm 25$ °C) inside the presumed recent caldera structure of the Piton des Neiges volcano, especially in the intrusive body areas of the Mât river, in Salazie, and in the Bras Rouge River, in Cilaos (area with the greatest development of hydrothermalism as an economic activity). After this restarted exploration phase, additional surveys (Anderson, 2005; Anderson, 2003; PB Power, 2003) were done, ending with a targeted drill site in La Plaine des Sables on Piton de la Fournaise (Fig. 1). However, this area had become part of the Parc National de La Réunion protected area and drilling, was no longer allowed and thus was not done.

3.2. Available geophysical data

Abundant geophysical data has been acquired on La Réunion Island since the 1970s (Fig. 3), including gravity (Gailler and Lénat, 2010; Lénat et al., 2000), magneto-tellurics – MT (Gérard and Stieltjes, 1979; Gérard and Rançon, 1981; Benderitter and Gérard, 1984; Geophyics, 2002; Geosystem, 2004; 2005; Anderson, 2005), self-potential – SP (Lénat et al., 2003b), heliborne magnetic, and transient electromagnetism (Martelet et al., 2014).

Gailler and Lénat (2010) compiled gravimetric and magnetic data and explored the three-dimensional structure of the submarine volcano, using joint gravity and magnetic modelling. The most complete Bouguer map is published in Gailler and Lénat (2012), who derived a general model of the island from a joint interpretation of available gravity, magnetic, and electromagnetic data. Lénat et al. (2003b) compiled about 8000 SP measurements of reasonable quality from various surveys conducted between 1981 and 2003 in La Plaine des Palmistes, La Plaine des Cafres, and Piton de la Fournaise.

Several magneto-telluric surveys have been performed since 1979, which provided about 300 soundings (Anderson, 2005). These data have been reviewed and an index has been attributed to each of them to qualify their depth investigation.

Table 1
Characteristics of geothermal exploration boreholes on La Reunion Island (location on Fig. 1).

Name	Borehole	Year	Altitude (m)	Depth (m)	Temperature (°C)
SGTH1	Roche Plate – Salazie thermal gradient borehole	1980	675	201	57
SGTH2	Piton Des Fées - Plaine Des Palmistes thermal gradient borehole	1980	1242	235.3	19.2
SGTH3	Grand Galet, right bank of Rivière Langevin thermal gradient borehole	1981	605	202.9	17.7
SGTH4	Rempart - Plaine Des Palmistes thermal gradient borehole	1981	1070	127.2	16.2
SGTH5	Grand Brulé - Vierge au Parasol thermal gradient borehole	1981	31	235.2	17.4
SR-1	Grand Brulé - Piton de la Fournaise deep geothermal borehole	1985	173.16	3003.5	143.7
SLZ1	Salazie - Mare à Vieille Place deep geothermal borehole	1986	795	2108	192 (extrapolated)

For this purpose, a conceptual model of a favorable high temperature geothermal site has been defined, which combines the typical resistivity model introduced by Johnston et al. (1992) with a positive gravity anomaly, which may correspond to the presence of a shallow depth heat source (Fig. 4). The model is characterized by a layered distribution of clay mineral assemblages, with their estimated thermal stability

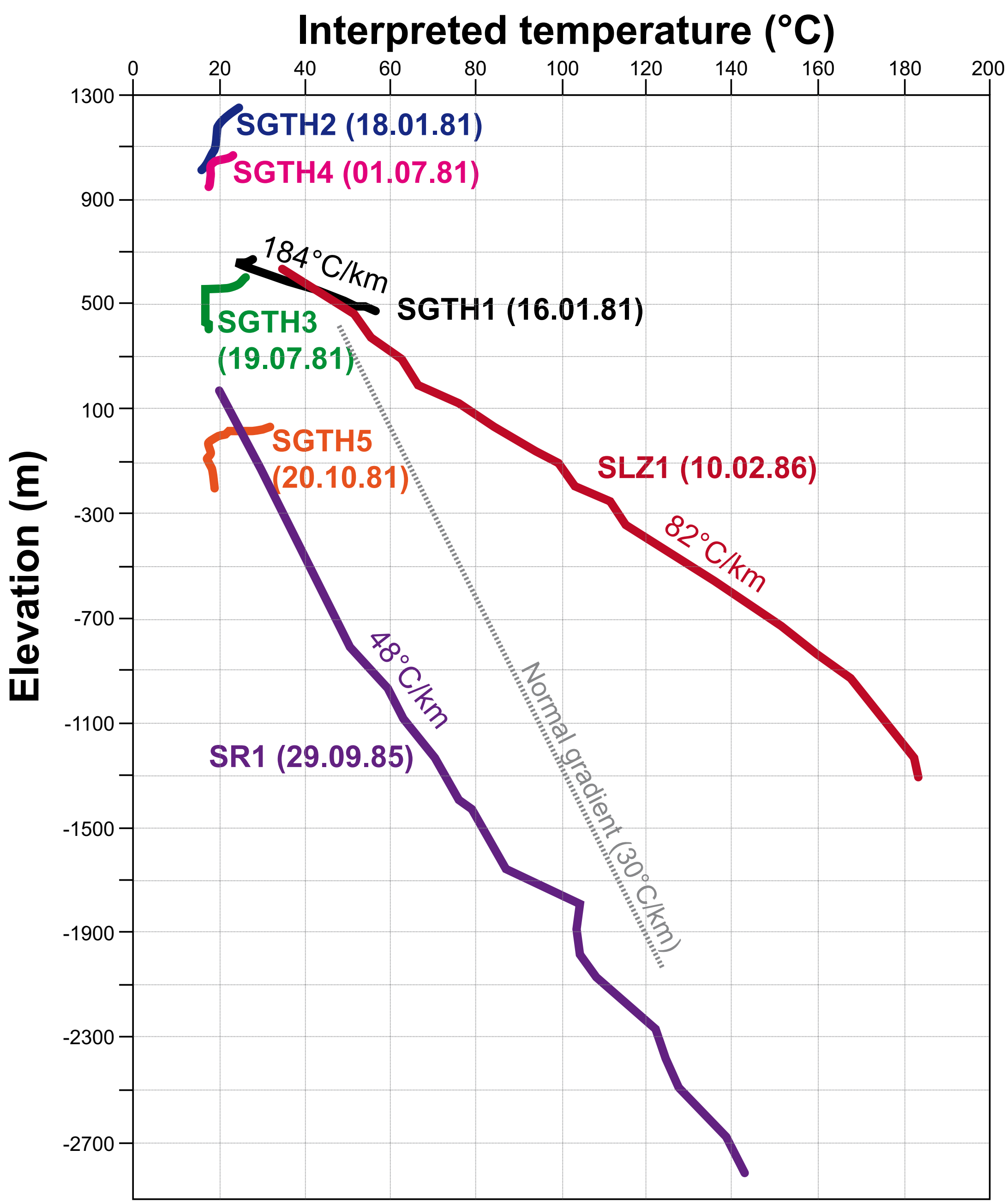

Fig. 2. Temperature gradient in the geothermal wells (modified from PB Power, 2002).

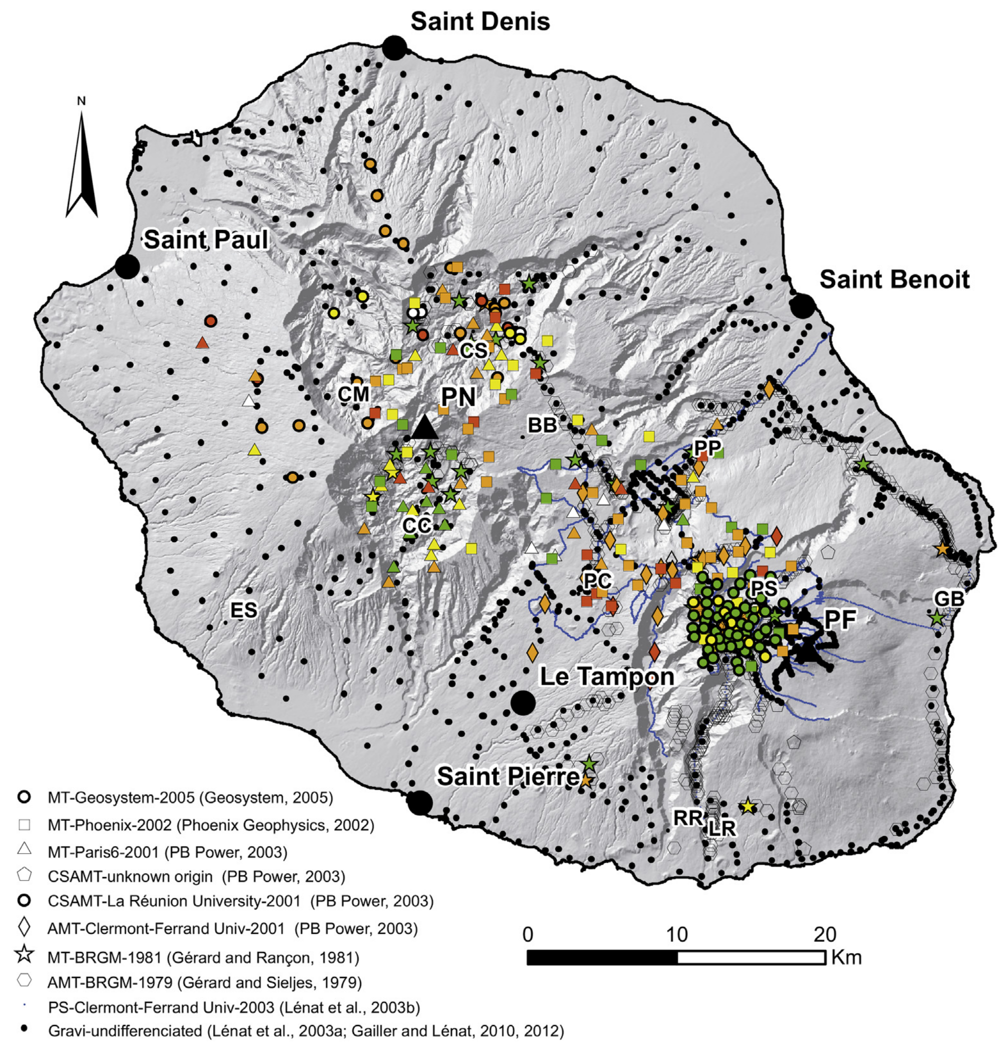

Fig. 3. Map of available geophysical data. the index of the various MT survey results (colors) is defined with reference to Fig. 4. colors: red: bad index, orange: poor index, yellow: average index, green: good index. (For interpretation of the references to colour in this fig. legend, the reader is referred to the web version of this article.)

ranges (Simmons and Browne, 1990). The alteration zone, called the clay cap, is usually easily detected by electromagnetic methods as a conductive layer (Johnston et al., 1992; Pellerin et al., 1996; Anderson et al., 2000; Ussher et al., 2000; Fig. 4). In addition to this model, we also consider the presence of a heat source, of which the geophysical response is often a positive gravity anomaly, because it is associated with a dense intrusion (Fig. 4). For this paper, this constitutes the so-called "common geothermal system". However, this approach is not perfect, because a gravity anomaly may correspond to a cold magmatic body whereas fossil and active geothermal systems may have the same typical resistivity signature. In other words, cold magmatic intrusions or fossil geothermal systems may be incorrectly identified as favorable sites.

Following a procedure similar to that used by Anderson (2005), an index based on the depth investigation results was applied. Based on the Johnston model (Johnston et al., 1992), a sounding that defines only the top of the clay cap is then considered poor, whereas a sounding detects resistivity below the clay cap is considered good (Fig. 4). When mapped, this classification shows that the areas with enough resistivity data to indicate a potential reservoir are the La Plaine de Sables area, with 3D coverage, and the cirques of Salazie and Cilaos (Fig. 3).

More recently, a heliborne magnetic and transient electromagnetism (TEM) survey covered 70% of the island (Martelet et al., 2014). Even though these data extend only to a depth of approximately 250 m, some cross-sections have been used to calibrate the resistivity response of the outcropping formation and to aid in the analysis and interpretation of zones of geothermal interest.

3.3. Data integration method

All data collected were entered into a Geographical Information System (GIS) to allow a GIS-based analysis using the weighted overlay method so as to select the most promising areas for geothermal resources (e.g. Prol-Ledesma, 2000; Noorollahi et al., 2008; Yousefi et al., 2010; Trumpy et al., 2015). This powerful tool aids in visualization of all types of localized data, can help in the production of new maps and allows a cross-analysis of data to aid in decision making (Noorollahi et al., 2007).

In the weighted overlay raster calculation method, input data have been reclassified into input rasters based on a common evaluation suitability scale (Noorollahi et al., 2007). Input rasters are weighted relative to their importance and added to produce the output raster (Fig. 5). Finally, the output raster shows the geothermal favorability areas.

In this study, outcropping plutonic rocks and volcanic cones are considered to be favorable indicators for the presence of a heat source at depth. Indeed, plutonic complexes constitute cooled magmatic reservoirs brought to the surface by erosion, and thus imply the existence of a near-surface magmatic system. Because volcanic cones are easily eroded landscape structures that are usually erased in less than

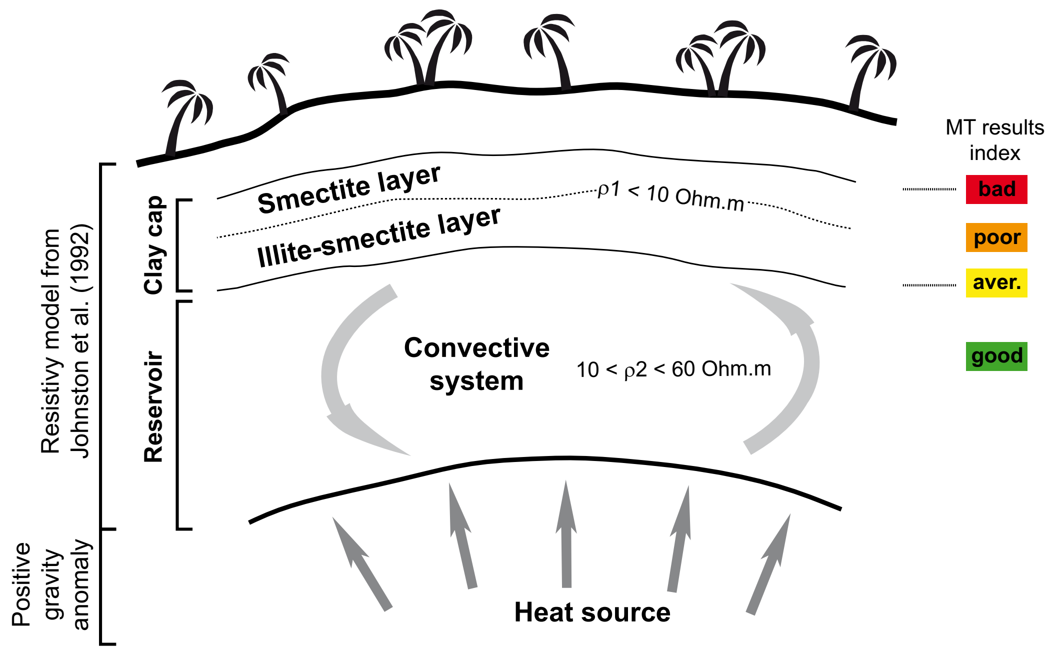

Fig. 4. Proposed geophysical model, based on resistivity and gravity results, for selecting favorable sites based on common geothermal systems. the MT index corresponds to the depth reached by the various MT surveys and used in the map in Fig. 3.

100 ka, their presence can be used to characterize recent volcanic activity, which in turn suggests a nearby heat source and the possibility that surface water may circulate in proximity to it.

The integration of these indications into the GIS is made on the basis of the vectorized 1/50000^e geological map. Plutonic outcrop polygons were buffered at 500 m and volcanic cones at 250 m (Fig. 5, Fig. 6-A). Buffer distances were selected on the basis of the subsurface spatial influence of these structures. We consider that at depth a gabbro pluton is at least three times larger than its surface outcrop. Because volcanic cones are more developed at the surface, we estimate that they are narrower than gabbros at depth.

The role of fractures, including faults, is also important in controlling subsurface fluid flow. However, these structures are challenging to locate in the tropical environment of La Réunion Island due to the vegetation, but several studies note the presence of fracture systems in the volcanic edifices of Piton des Neiges and Piton de la Fournaise, which are located within rift zones or in their vicinity (Chaput et al., 2017, 2014; Chevallier and Bachelery, 1981; Chevallier and Vatin-Perignon, 1982). Other possible fluid flow pathways are planar intrusions, such as dykes or sills. These structures are weakness zones where fluid can circulate downward (*per descendum*) and/or upward (*per ascensum*). The locations of these potential fluid pathways, based on literature, are included as contoured areas in the GIS (Fig. 5, Fig. 6-A).

Indicators of hydrothermal activity include hydrothermal alteration zones, fumaroles, travertines, and hot springs. Fumaroles and travertines indicate hot fluid outflow even if they are inactive and fossilized. The primary indicators of hot fluid circulation are hot springs that have a discharge temperature at least 5 °C higher than nearby surface water, electrical conductivity greater than 200 μS/cm, and/or pH that is lower by at least one unit indicator. Geochemical analysis of these waters provides a wealth of information, such as fluid origin, the temperature of equilibrium with deeper rocks and thus the maximum fluid depth, and fluid residence time. The location and distribution of hydrothermal zones (fumaroles, travertines and hot springs) are used to

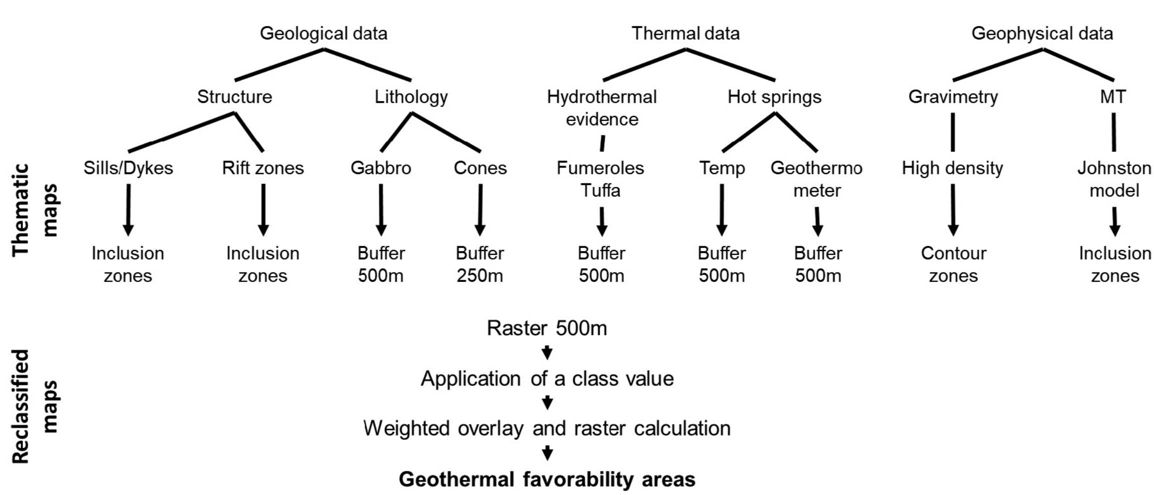

Fig. 5. Flow diagram to generate geothermal favorability maps.

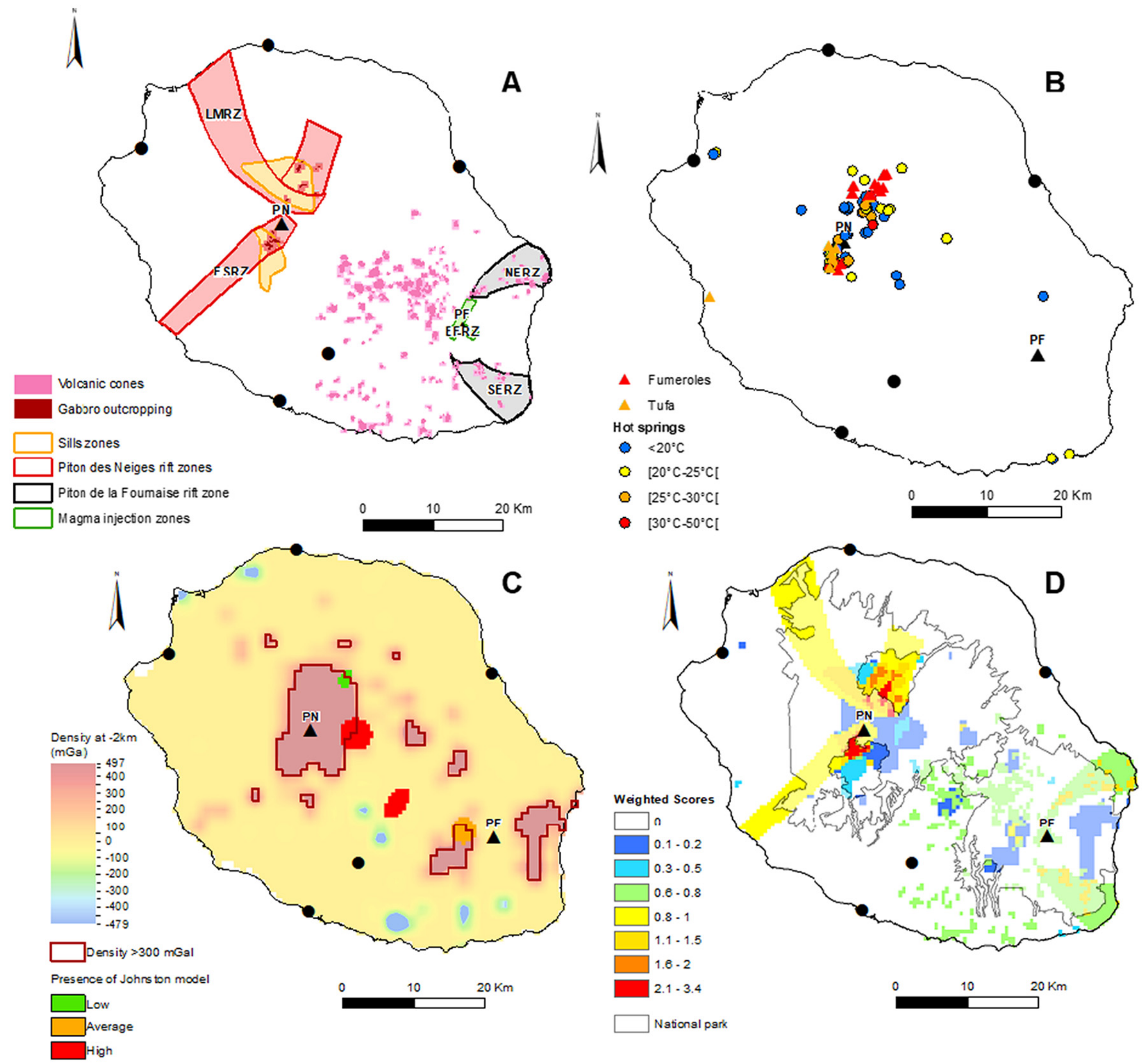

Fig. 6. Data and thematic maps for (A) geological indicators, (B) hydro-thermal indicators, (C) geophysical indicators, and (D) resulting weighted map. Black points: main towns. black triangles: summits of Piton des Neiges (PN) and Piton de la Fournaise (PF).

identify potential geothermal areas, because geothermal resources can occur in the vicinity of these hydrothermal activity indicators. In our statistical analysis, as these components are defined as a point location, a buffer has been applied with an arbitrary distance of 500 m (Fig. 5, Fig. 6-B). This buffer distance does not reflect the exact influence of hot fluid at depth but facilitates the raster calculation.

Numerous geophysical surveys, especially gravity and electromagnetic surveys, have been conducted since the 1970's (cf. §3.2). Gravity surveys provide information about rock density integrated over a wide depth measurement interval; high-density rocks yield positive gravity anomalies whereas low-density rocks yield negative gravity anomalies. In an intraplate volcanic context such as La Réunion Island, high-density rocks are generally formed in intrusive systems by slow crystallization of magmas whereas low-density rocks correspond to extrusive volcanic formations such as lava flows, ashes, scoria hyaloclastites or to sedimentary rocks such as alluvial deposits or breccia (Gailler and Lénat, 2012). In our statistical analysis, we have thus considered values higher than 300 mGal to indicate a hypovolcanic intrusive complex, i.e. a shallow paleo magmatic reservoir. The hypovolcanic intrusive complexes are contoured areas in the GIS (Fig. 5, Fig. 6-C).

To integrate electro-magnetic surveys into our analysis, we have also considered the data interpretation used in the Johnston model (Johnston et al., 1992) of a common geothermal reservoir (Fig. 4). We used numerous surveys and data analyses to determine zones where the model can be applied and we have defined three probabilistic levels: 1) high probability when the data satisfy the Johnston model of a clay cap (conductive layer) above a sufficiently thick reservoir that supports the convection loop; 2) average probability if the MT inversion results give a 50% probability of having a reservoir; 3) low probability if the conductive layer is absent or not thick enough. These three probabilistic levels have been included in the GIS as colored fields (Fig. 5, Fig. 6-C).

4. Analysis of thematic maps

4.1. Geological layer

Geologic studies play an important role in geothermal exploration stages to characterize the host reservoir and evaluate its properties as an analogue of subsurface reservoirs, and to aid in interpreting data from other exploration methods such as geophysical surveys. Surface geology is also important for indicating subsurface lithology and the presence of reservoirs or heat sources. The presence and distribution of plutons and planar intrusions, volcanic cones, hydrothermal alteration, fractures, and faults are the primary geological data used to guide geothermal exploration; they can also be used in the geological indicator layers. Plutonic rocks observed at La Réunion Island include gabbros, peridotites, and syenites that crop out in river beds of the cirques of Salazie and Cilaos (Fig. 6-A), or are encountered in the deep scientific drillings SZ1 and SR1. For planar intrusions (Fig. 6-A), we used the distribution by Chaput et al. (2017) for Piton des Neiges (two sill zones and two rift zones N30°E and N120–160°E) and that of Michon et al. (2007) for Piton de la Fournaise (two arcuate rift zones and an N120°E rift zone). Volcanic cones are primarily located between Piton des Neiges and Piton de la Fournaise in the southern part of Piton de la Fournaise (Fig. 6-A). Hydrothermal alteration in the low greenschist to prehnite-pumpellyite facies is primarily observed in cirques (Rançon et al., 1985). Fractures and faults are also mainly observed in the cirques, but they are also present in sill and rift zones (Chaput et al., 2017).

4.2. Hydrothermal activity layer

Surface hydrothermal activity is an important indicator regarding the presence of a subsurface geothermal system. In La Réunion, thermal springs, fumaroles, and tufas are almost exclusively located on Piton des Neiges (Fig. 6-B). However, the temperature of the thermal springs is not high, mainly between 20 °C and 30 °C. The hottest spring (48 °C) is located in the cirque of Cilaos. A single thermal spring has been found on Piton de la Fournaise, in the rivière de l'Est tunnel, with a temperature lower than 25 °C (Fig. 6-B). Like the thermal springs, fumaroles and tufas are located in the cirques of Salazie and Cilaos. Only one tufa has been found on the western coast of the island, as described in Billard (1974).

4.3. Geophysical layer

Geophysical surveys, which are important for the visualization of subsurface geological formations, may also be used to detect the presence of fluids and/or fluid flow at depth. However, the geological interpretation of geophysical data is non-unique, and this non-uniqueness must be taken into account.

Gravity surveys indicate the presence of high-density rocks under the summit of Piton des Neiges (Fig. 6-C). Other high-density rock zones are located on the eastern and western flank of Piton de la Fournaise and between the two volcanoes, in the Plaine des Palmistes (Fig. 6-C).

Interpretation of MT data in terms of the common geothermal reservoir (Johnston et al., 1992) shows that the best probability locations are found in the eastern part of Piton des Neiges and between the two volcanoes in the Plaine des Cafres (Fig. 6-C). At the eastern part of Piton de La Fournaise, probability is average and corresponds to the presence of high-density rocks (Fig. 6-C).

5. Data integration

Favorable areas at La Réunion Island have been defined in terms of the probability of finding a geothermal reservoir using the three thematic digital maps defined above, that is, including a geological layer, a hydrothermal activity layer, and a geophysical layer. A class value has been applied to each variable of the different thematic maps in relation to the geothermal suitability of these variables. A scale from 1 to 3 was chosen, the highest value being the most suitable (Table 2).

In the next step, a weight was assigned based on the impact of each thematic map in the geothermal favorability model (Table 2). This weight constitutes a percentage of the total of the thematic maps and the distribution is made by considering the impact of each parameter.

Geological data and geothermometer values are the primary indicators for identifying a geothermal reservoir; therefore, they have maximum impact. We thus assign a weight of 30% to these indicators (Table 2). A strong correlation exists between geothermal occurrences and thermal springs, but the temperature values at La Réunion Island are low. As a result, we assign a weight of 20% to the presence of thermal springs as a geothermal resource indicator (Table 2). Hydrothermal indicators are also encouraging signs, but most are fossilized and of unknown age. Thus, we give them a weight of 10% (Table 2). Because geophysical data are strongly dependent on tools, models, and interpretations, we attribute a weight of 5% to Bouguer gravity and to the application of the Johnston model via MT analysis (Table 2).

These weights are applied to each map when combining the raster layers by addition of the cells. The generated map is subdivided into seven classes, with weighted scores from 0 to 3.4 (Fig. 6-D). The highest values correspond to the most likely zones for the geothermal exploitation, which are discussed below.

6. Favorability area analysis

To locate a place name, refer to Fig. 1.

6.1. Cirque of Salazie

The cirque of Salazie has been studied extensively, both for geothermal exploration and for scientific objectives. Two boreholes (SGTH1, 201 m deep, and SLZ1, with a depth of 2108 m, Table 1) show a high thermal gradient, ≥ 85 °C/km, nearly three times the thermal gradient of stable continental crust (Fig. 2). However, hydraulic tests in SLZ1 collapsed the borehole at a depth of 541 m under the casing shoe, which indicated low permeability that precluded economic production at that time. CO_2-rich thermal springs and very recent fumaroles are observed in the cirque of Salazie, in addition to mercury anomalies (Rocher et al., 1987). Oxygen and hydrogen isotopic signatures indicate that water from thermal springs in the Mât river area are of meteoric origin, like other thermal springs at La Réunion island (Bénard et al., 2020). The maximum temperature at depth computed using chemical and isotope geothermometers is 100 ± 20 °C, suggesting a relatively near-surface hydrothermal system (Sanjuan et al., 2001).

The plutonic complex that is penetrated by SLZ1 and that crops out in the Mât river is a frozen intrusive complex of Piton des Neiges (Berthod et al., 2020). This body and the overburden of basic breccia and basaltic lavas have low porosity as a result of a succession of at least three phases of secondary mineral precipitation (serpentine+chlorite, then zeolite, then calcite; Famin et al., 2016). However, these rocks are highly fractured with a dominant population of normal faults oriented N100°*E*-N120°E (Chaput et al., 2017; Chaput et al., 2014). These faults are associated with the activity of the La Montagne rift zone and the Salazie sill zone (Fig. 6-A).

Analysis of the 2D MT section (Anderson, 2003; PB Power, 2002) combined with geological input (Chaput, 2013) and the high-resolution HeliTEM 3D model (Martelet et al., 2014) confirms the existence of a fossil geothermal reservoir. PB Power (2002) and Anderson (2003) noted that in most of the cirque of Salazie, the thickness between the conductive cap rock and the high-density volcanic hypostructure may not be sufficient to permit development of a convective plume, as is usual in a common geothermal system. A more conductive area was nevertheless confirmed by HeliTEM data (Martelet et al., 2014) south of the cirque where thermal springs are most abundant. This dense and conductive zone may constitute a permeable layer that could favor hydrothermal fluid circulation without indicating the presence of a classical geothermal reservoir. All these elements converge south of the cirque of Salazie, near the central part of Piton des Neiges, making it an area of high interest.

6.2. Cirque of Cilaos

The cirque of Cilaos has a configuration similar to the cirque of Salazie, with the presence of the Etang Salé rift zone and a sill zone Fig. 6-A). Although no geothermal borehole has been drilled in this area, a well drilled for water resource exploration reached a depth of

Table 2
Class values used for geothermal indicators and weight used for each thematic map.

			Class values			Weight
	Thematic layers		1 Low	2	3 High	
Geological data	Structures					30%
	Presence of	Sill zone	X			
		Rift zones of Piton des Neiges			X	
		Rift zones of Piton de la Fournaise		X		
	Lithology					
	Presence of	Volcanic pitons		X		
		Plutonic rocks	X			
Thermal data	Hydrothermal indices					10%
	Presence of	Tufa, fumeroles			X	
	Hot springs					
		Discharge temperature	[20–25 °C[	[25–30 °C[	[30–50 °C]	20%
		Geothermometer value	[20–70 °C[	[70–100 °C[	[100–150 °C]	30%
Geophysical data	Bouguer (mGal)			>300		5%
	Johnston model					5%
		Salazie	X			
		Bébour-Bélouve			X	
		Plaine des Cafres			X	
		Plaine des Sables		X		

350 m. A temperature of 23 °C was measured at a depth of 116.3 m in this well (Fig. 6-B). Even though the measurement procedure is not known, this result suggests a thermal gradient equivalent to that measured in the cirque of Salazie, i.e. around 85 °C/km.

CO_2-rich thermal springs and very recent fumaroles are concentrated in the northern part of the cirque, close to the Piton des Neiges summit (Fig. 6-B). A maximum at-depth temperature of 130 °C ± 25 °C was estimated for thermal waters, using chemical and isotope geothermometers (Sanjuan et al., 2001). Moreover, soil-gas anomalies (CO_2, He, Rd) are present northwest of the cirque (Ilet Chicot and Ilet à Cordes; Fig. 1), providing evidence of deep fluid circulation (Sanjuan et al., 2001).

2D MT sections (Anderson, 2003; PB Power, 2002) and the 3D gravity model (Gailler and Lénat, 2012) show a dense hypostructure under a conductive layer. Although the thickness of the conductive layer here appears to be twice that of the cirque of Salazie, it may still be insufficient for the development of a large classical geothermal system.

The cirque of Cilaos therefore constitutes a zone of high interest in the northern part, close to the summit of Piton des Neiges However, the difficult conditions of access to this area must be taken into account when considering future explorative investigations.

6.3. La Plaine des Cafres

This area is located between the two volcanoes, near an urbanized zone. It would therefore be of interest for the development of geothermal projects if favorable indicators are found. Several soil-gas measurement studies have indicated an anomaly in one or two of the three gases measured (CO_2, He, Rn; Liuzzo et al., 2015; Boudoire et al., 2017). The density of recent volcanic cones is elevated (Di Muro et al., 2012), but no present-day surface volcanic manifestations, such as fumaroles or hot springs, have been observed in this zone.

MT profiles across this area (PB Power, 2003) show a resistivity signature that may be associated with a common geothermal system. However, the data are of variable quality and coverage is poor. Also, the conductive cap seems discontinuous and of limited extent. In addition, the gravity survey did not detect a dense body similar to those detected under the cirques of Salazie and Cilaos (Lénat et al., 2003a). This system needs improved definition through additional geophysical investigation.

6.4. La Plaine des Palmistes

Two gradient wells were drilled in La Plaine des Palmistes, near La Plaine des Cafres (SGTH2 and SGTH4; Fig. 1, Table 1). In these wells, which are 235.3 m and 127.2 m deep, respectively, temperatures measured at well bottoms are 19.2 °C and 16.6 °C, respectively (Table 1). No present-day surface volcanic manifestation is observed. However, soil-gas measurements show a significant Rn anomaly at one location. MT data does not show sizeable conductive layer, which does not argue in favor of a common geothermal system.

6.5. La Montagne and Etang Salé rift zones

Chaput et al. (2017) concluded that the La Montagne rift zone was active during the shield building stage of Piton des Neiges (≥ 430 ka), and that activity ceased afterwards. Even so, the Etang Salé area is a large regional rift zone, which could involve the oceanic crust and allow deep fluid circulation. This rift zone was active in the differentiated stage (≤ 370 ka, i.e. PN3 or PN4 periods) of Piton des Neiges (Chaput et al., 2017). Recent volcanic cones (Michon et al., 2015) and sinter (Billard, 1974) are present in this area. However, these volcanic products have not been exhaustively dated by radiometric methods. Likewise, no geophysical data are available in this sector, with the exception of one gravity and heliborne geophysical survey (Martelet et al., 2014). The gravity model shows high-density structures in this area, which could indicate volcanic hypostructures (Fig. 4; Lénat et al., 2003a) and potential heat sources.

6.6. Piton de la Fournaise rrift zones

The two boreholes drilled in the vicinity of the NE arcuate rift zone at Piton de la Fournaise (SGTH5 and SR1) show no evidence for high temperature gradients or fluid circulation (Fig. 2, Table 1). The few elements of geophysical data that are available for this area show no characteristic signature of a classical geothermal system. Gravity models (Gailler et al., 2009; Lénat et al., 2003b; Rousset et al., 1989) consistently indicate a dense body corresponding to the plutonic complex of the Grand Brûlé that was reached by drilling (SR1). Given the moderate thermal gradient, this plutonic complex does not constitute a heat source. There is thus no encouraging indicator for a geothermal potential in this zone.

6.7. La Plaine des Sables

This area is the northwestern part of Piton de la Fournaise and a former caldera of the volcano (Fig. 4). After the survey performed in the 2000s, La Plaine des Sables was designated as La Réunion Island's most favorable site on the basis of the following converging geophysical results (Anderson, 2003):

1. the MT survey highlights a domed low-resistivity layer typical of a classical geothermal system;
2. gravimetry measurements show a dense anomaly at shallow depth that may correspond to a potential heat source;
3. the presence of a positive SP anomaly, even though located far from the presumed target, could/may indicate a vertical *per ascensum* geothermal flow.

Because of these promising indicators, an additional high quality 3D MT survey was performed and a geophysical inversion with different parameters shows that a classical geothermal system may be present, with a 50% probability (Anderson, 2005). No hot springs or fumaroles are observed, but evidence indicates recent volcanism in this area in the past 5.5 ka (Ort et al., 2016). A borehole planned in 2005 to confirm or deny the geothermal resource of this zone was cancelled because of its location within the National Park and the classification of La Réunion Island as a UNESCO World Heritage Site.

6.8. Langevin and Remparts rivers

These two rivers incise the southern flank of Piton de la Fournaise, south of La Plaine des Sables (Fig. 1). It has been proposed that a borehole from the head valleys of these rivers (outside the National Park) could reach the geothermal system identified by Anderson (2003) under La Plaine des Sables. However, the target appears to be too distant for a borehole and, furthermore, access to these valleys is difficult for large vehicles.

Apart from this option, some exploration has been done in this area. The low bottom temperature of the gradient well in Rivière Langevin (SGTH3) is not a promising indicator (Fig. 2, Table 1). Springs are present but no reliable chemical analysis is available for them. No recent surface volcanic manifestation is observed. The gravity anomaly identified under La Plaine des Sables continues beneath SGTH3 and appears stronger, mainly due to the presence of the deep valley (Fig. 4; Lénat et al., 2003b). Vintage geophysical data that are available show a conductive layer in this area (Gérard et al., 1981). However, these scarce data do not show the characteristic signature of a classical geothermal system.

6.9. Bébour-Bélouve

This paleo-cirque, southeast of Piton des Neiges but outside present-day cirques, is not covered by any MT survey. Nevertheless, the conductive layer identified in the eastern part of Piton des Neiges (Gailler and Lénat, 2012) likely continues toward the east. The extent and deepening of the Piton des Neiges hypostructure shown by the 3D density model (Lénat et al., 2003a) would imply a widening of the gap between the top of the hypostructure and the bottom of the conductive layer. This gap could be wide enough to allow the development of a convective geothermal system. Moreover, a thermal spring far east of this area (Fig. 1) yielded a deep temperature estimated at 130 ± 25 °C, using classical and auxiliary chemical geothermometers (Sanjuan et al., 2001). A more detailed survey is necessary to determine the geothermal resource of this area, but the area is located within the National Park and access is difficult.

7. Discussion

A large part of La Reunion Island was classified as a UNESCO World Heritage Site in 2010 and as a result, many activities are now highly regulated within the National Park, including geothermal exploitation. Therefore, even though the La Plaine des Sables and Bébour-Bélouve sites have high scores and are promising candidates for geothermal exploitation (Fig. 6-D), no projects can be developed in these areas at this time.

Several signs indicate that the vicinity of center of the Piton des Neiges volcano is a favorable area for the development of medium to high temperature geothermal energy (cirques of Salazie and Cilaos; Fig. 6-D).

Other areas that are not in the National Park (Plaine des Cafres, Plaine des Palmistes, Etang Salé, rift zones of Piton de la Fournaise, Langevin and Rempart rivers) could/may prove interesting, but the amount of data is not yet sufficient to evaluate their geothermal resources. Further geological, geophysical, and geochemical investigations will need to be conducted in the future to confirm the geothermal resources in these areas. Therefore, the various favorable areas can be grouped into three main classes (Fig. 7): 1) areas with high geothermal potential, with abundant data, previous studies and converging results; 2) areas whose potential needs to be confirmed, for which sparse but interesting data exists, but which require further investigation; and 3) areas that have geothermal potential but are located within the National Park.

Despite the presence of two volcanoes, one of which is active, geothermal exploitation on La Réunion Island is not equivalent to that of Bouillante in Guadeloupe, Taupo in New Zealand, Puna in Hawaii or in other volcanic areas around the world. The volcanic setting of La Réunuion – intra-oceanic volcanic islands formed by multiple shield volcanoes – is the same as that of Hawaii (Peltier et al., 2015). Piton de la Fournaise and Hawaii's Kilauea are among the world's most active volcanoes. A geothermal reservoir has been located on the side of Kilauea, inside a 100 km long and 2–3 km wide rift zone (half of it below sea level). Fissural volcanic emissions, seismo-tectonic activity and the presence of normal faults indicate the extent of this structure. Geothermal exploration began in the 1960s and geothermal exploitation started in 1993 (Gardner et al., 1995). Despite the presence of a high-temperature resource, permeability conditions were not sufficiently homogeneous and development of a geothermal reservoir inside the rift zone was difficult to locate. The productivity of many boreholes (approximately 20 out of 24) was too low to permit any exploitation (Di Pippo, 1995). Lastly, a geothermal power plant, using two production wells and three injection wells, began operating in 1993 at Puna. It had a production capacity of 38 MWe (Bertani, 2016) before the 2018 Kilauea eruption destroyed it.

As in the case of Kilauea, the La Réunion Island volcanoes have rift zones on their flanks and deep deformation inside the edifices (e.g. Froger et al., 2015; Michon et al., 2016; Chaput et al., 2017). Such structures may favor fluid circulation at depth. However, the La Réunion Island rift zones are more diffuse than those of Kilauea.

Moreover, if we refer to the conceptual model of a common geothermal system, our compilation of previous geophysical surveys on La Réunion Island shows that the typical conductive layer is not continuous (for example: La Plaine des Cafres, La Plaine des Palmistes, the rift zones of Piton de la Fournaise) or is too thin for the development of large convective cells (as at the cirques of Salazie and Cilaos). It therefore appears that the probability of finding a classical geothermal system in La Réunion Island is low.

Even so, several elements – such as the thermal gradient, the presence of thermal waters and their temperatures at depth, estimated using chemical and isotope geothermometers, in addition to abundant magmatic CO_2 emanations – suggest that relatively high temperatures and fluid circulation may be present at depth, particularly in the Piton des Neiges area. Despite insufficient productivity in the 1980's to operate the SLZ1well in the cirque of Salazie, geological formations within Piton des Neiges appear to be highly fractured (Chaput et al., 2017, 2014). This implies that the permeability of the deep formations has not been thoroughly evaluated. All these lines of evidence suggest that permeability and fluid circulation may be found in deeper parts of the cirques.

To develop geothermal exploitation in this less favorable volcanic environment, a novel concept such as enhanced geothermal systems (EGS) would have to be considered so as to increase well performance in terms of productivity. Even though EGS technologies are primarily used in basement and deep sedimentary basin settings, they can also

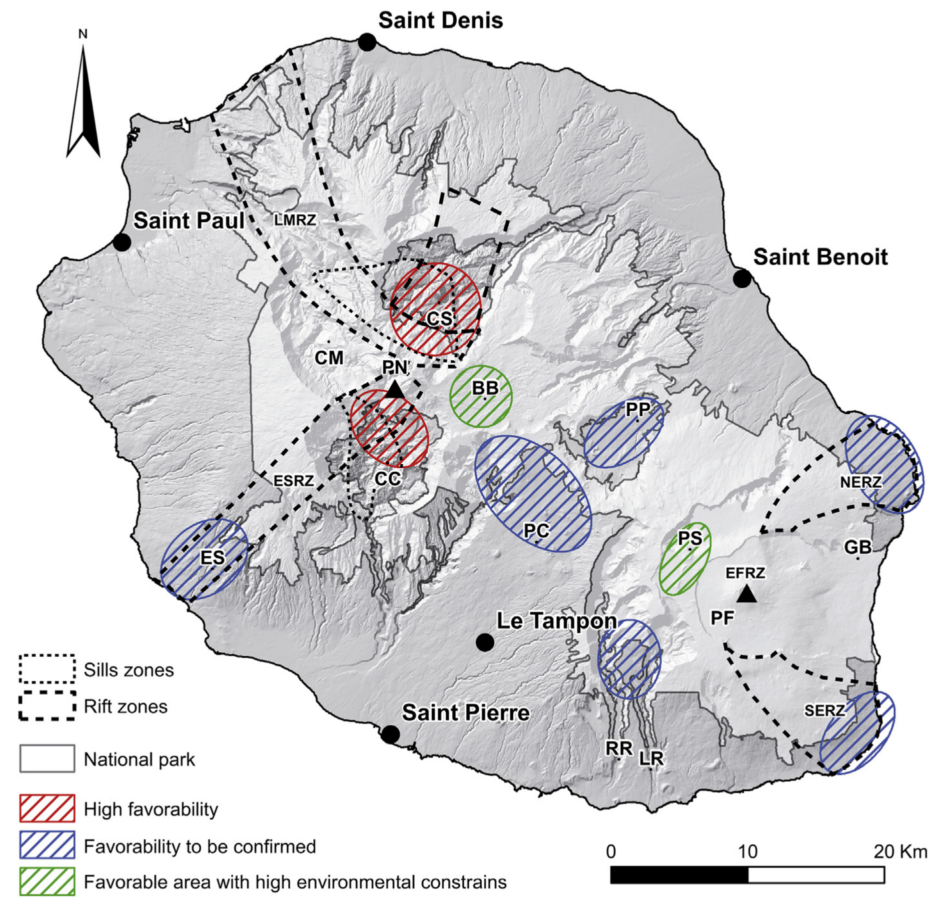

Fig. 7. Areas of interest for geothermal energy on La Réunion Island. CS: Cirque of Salazie; CM: Cirque of Mafate; CC: Cirque of Cilaos; BB: Bébour-Bélouve; PC: Plaine des Cafres; PP: Plaine des Palmistes; PS: Plaine des Sables; GB: Grand Brulé, LR: Langevin River; RR; Rempart River. LMRZ: La Montagne Rift Zone; ESRZ: Etang salé Rift Zone; EFRZ: Enclos Fouqué Rift Zone; NERZ: North-East Piton de la Fournaise Rift Zone; SERZ: South-East Piton de la Fournaise Rift Zone.

be used in other hydrothermal contexts to optimize exploitation. For example, the Newberry volcano in Oregon (USA), is a large shield volcano where geothermal boreholes indicate high temperatures (>315 °C at 3000 m) but no geothermal fluid is present. Based on these results and on complementary geological studies, EGS technologies have been used at Newberry, with the intention of enhancing, or even creating, a geothermal reservoir through thermal and hydraulic stimulation (Cladouhos et al., 2016). Future geothermal investigation in La Réunion will have to assess the feasibility of applying these EGS technologies to the areas of potential interest identified in this study.

8. Conclusions

This updated synthesis of approximately 40 years of geothermal research on La Réunion Island, coupled with an innovative GIS analysis, highlights multiple targets that we separated into three categories of decreasing interest (Fig. 7):

1. Areas of interest, such as the cirques of Salazie and Cilaos, which present a combination of favorable indicators. The geothermal clues show that the southern part of the cirque of Salazie and the northern part of the cirque of Cilaos (i.e. areas near the summit of the Piton des Neiges volcano) are the most promising zones. Future exploration in these areas will require an exploration borehole.
2. Areas of interest to be confirmed, such as La Plaine des Cafres, La Plaine des Palmistes, the Etang Salé rift zone, the NE and SE rift zones of Piton de la Fournaise, and the Langevin and Remparts rivers. These zones have favorable indicators but have not yet been thoroughly investigated. In these cases, additional surveys are needed to evaluate the resource accurately.
3. Areas of interest within the National Park, which is classified as a UNESCO World Heritage Site, such as La Plaine des Sables and the Bébour-Bélouve paleo-cirque. These areas may warrant further investigation, but their location does not currently allow development of geothermal projects.

We have shown that thermal anomalies are present but that permeability seems insufficient for common geothermal reservoir exploitation. Therefore, future exploration work should consider this specific aspect and explore other criteria, such as discontinuities, stress states, fluid pathways, and should also evaluate the possibility of enhanced capacity gained from use of EGS technologies to reach viability.

Author contributions

C. Dezayes, V. Famin, B. Tourlière, J.-M. Baltassat have contributed to the conception and design of the study.

C. Dezayes, V. Famin, B. Tourlière, J.-M. Baltassat, B. Bénard have contributes to the acquisition of the data.

C. Dezayes, V. Famin, B. Tourlière, J.-M. Baltassat have contributes to the analysis and interpretation of data.

C. Dezayes wrote majoritary the manuscript with the help of V. Famin.

V. Famin, B. Tourlière, J.-M. Baltassat, B. Bénard revised the manuscript.

All authors approve the publication of the manuscript.

Declaration of Competing Interest

None.

Acknowledgements

This study was cofounded by ADEME (French Energy Agency) and DEAL (Direction of Environment, Development and Housing). The authors would like to thank Jean-François Cousin and Matthieu Waeselynck from ADEME, and Samuel Laslandes from DEAL for their fruitful discussions in the steering committee. We also thank Rémy Durand from the Conseil Régional de La Réunion (Regional Council) for his help in the access to archival data. The authors greatly appreciate discussions with Jean-Philippe Rançon, Philippe Rocher, Bernard Sanjuan, Bertrand Aunay, and Séverine Bes de Berc, which were helpful to the success of the project. The authors are also thankful to Patrick Bachèlery and other anonymous reviewer whose recommendations helped to improve substantially the manuscript. We also thank Patricia Bobeck for help in polishing the English.

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