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Imaging of a Geothermal Reservoir in Volcanic Environment with Magnetic Data Supported by Structural and Petrophysical Analyses

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ABSTRACT

The GEOTREF Program aims to develop new concepts for the prospection of high enthalpy geothermal reservoirs in volcanic environments. The main target of the program is in Basse-Terre Island, Guadeloupe, French West Indies.

One of the main ways to assert a conceptual model for this kind of reservoirs is to analyze an analogue outcrop developed in similar conditions than those expected for the prospected one. The studied analogue is in Terre-de-Haut Island, in Les Saintes archipelago, 15 km south to Basse-Terre. The central part of the island displays highly hydrothermalized materials surrounded by fresh or weakly altered materials. The structural analysis conducted onshore highlights three structural directions controlling the shape of the reservoir and the main pathways for hydrothermal circulation. The most altered material is located at the intersection of two structural directions, mainly N-S and E-W. From this area, faults control propagation of the hydrothermal fluid far from the main reservoir.

Hydrothermal processes alter the magnetized minerals of volcanic rocks hence the measurements of the magnetic susceptibility along outcrops show very low values of magnetic susceptibility for hydrothermalized samples (0.01 to $0.1 \cdot 10^{-3}$ SI) while fresh materials have significantly higher values (around $10 \cdot 10^{-3}$ SI). A new acquisition method is developed to acquire offshore magnetic data with high resolution. The magnetic map acquired around the island shows important variations of the magnetic susceptibility value with strong consistency with the onshore structural mapping. The magnetic study allows to understand the offshore extent of the reservoir.

Within the project, airborne UAV magnetic data were also acquired over the island of Basse-Terre where the main geothermal target lies.

1. INTRODUCTION

Recent volcanic environments like the Caribbean are key targets for geothermal prospecting because they are usually associated with high surface heat flows and fracture networks that allow for fluid circulation at depth. In Guadeloupe, the site of Bouillante in Basse-Terre has been exploited since the 1980s (Sanjuan and Traineau, 2008) for electricity production. To comply with the recent French environmental decrees, a permit has been filed south of Bouillante in the Vieux-Habitants area, associated with the innovative research program GEOTREF. This project benefits from the 'Investments for the Future' program from the French government and one of its objectives is to propose new methods for the investigation of reservoirs in volcanic settings. Several presentations from the GEOTREF team are proposed within the WGC 2020.

The geophysical imaging of such reservoirs often includes seismic and/or electromagnetic methods. In the context of the Basse-Terre Island, onshore seismic studies are demanding due to the topography, vegetation and surface materials. In such an environment, high resolution non-seismic prospecting can be decisive to understand the extension and geometry of fractured reservoirs in volcanic settings. In this study, the contribution that can be brought by the magnetic method is investigated. An essential preliminary study for geophysical interpretation consists in tectonic, petrographic and petrophysical characterization of the target area. The detailed analyses of theses aspects are discussed in a separate presentation as part of the WGC 2020.

The approach first includes an analysis of the surface analogue in the Les Saintes archipelago, in the south of Basse-Terre. The altered materials in the exhumed reservoir of Terre-de-Haut, Les Saintes, exhibit weak magnetizations compared with the otherwise fresh volcanic materials. Considering these results, magnetic studies of this area can bring understanding of the hydrothermally altered materials that underly the Les Saintes reef plateau offshore the island. Because the area to be surveyed is shallow and near the coasts, a specially designed magnetic survey method is developed to acquire high-resolution marine data. Interpretation is carried out with reduction to the pole analysis and *via* an inverse filtering method in the spectral domain. The latter can be applied due to the special conditions of acquisition and the geological context of the offshore part of the studied area. The marine extrapolation of the demagnetized area is discussed. The combination of all the available data leads to the establishment of a conceptual model for this paleo-reservoir.

The results of the analogue study lead to the analysis of the Vieux-Habitants target. In this case, however, the reservoir is not exhumed and is still active. The magnetic measuring equipment is carried by a drone and this innovative acquisition set-up is discussed. Due to different factors, the interpretation cannot be achieved with the same filtering as for the analogue study. Magnetic map transforms are examined in relation to the structural knowledge of the area.

2. GEOLOGICAL CONTEXT

The western part of the Guadeloupe archipelago is included in an active volcanic system produced by the slow rate subduction of the North American plate under the Caribbean plate (Bouysse and Westercamp, 1988; DeMets et al., 2000).

The Basse-Terre Island is thus characterized by effusive volcanism and displays massive lava flows and domes as well as pyroclastic formations with debris flows and lahars. South of Basse-Terre, Les Saintes archipelago exhibits similar materials except in the central part of the Terre-de-Haut Island, where intense hydrothermal transformations are recognized (Verati et al., 2016). The emplacement of the Island, the composition of the materials and the estimation of the activity period of this hydrothermal system lead to the conclusion that this area in Terre-de-Haut is an exhumed geothermal reservoir that is analogous to the Basse-Terre geothermal reservoir (Jacques et al., 1984; Zami et al., 2014, Samper et al. 2007, Verati et al. 2016, Favier et al., 2020).

At a regional scale, the Guadeloupe archipelago is located at the intersection of four major structural orientations: the grabens of Les Saintes (N10-160), of Bertrand-Falmouth (N50-N70) and of Marie Galante (N90-N110), and the transtensive zone of Montserrat-Bouillante (N120-N140).

3. STUDY OF TERRE-DE-HAUT PALEO-GEOTHERMAL RESERVOIR

The mapping carried out by Verati et al. (2016), Navelot (2018), Navelot et al. (2018) and summarized by Géraud et al. (2020) show the importance of E-W and N-S structures on the island's structure. Two other directional families are also present: N120-N140 and N40-N60.

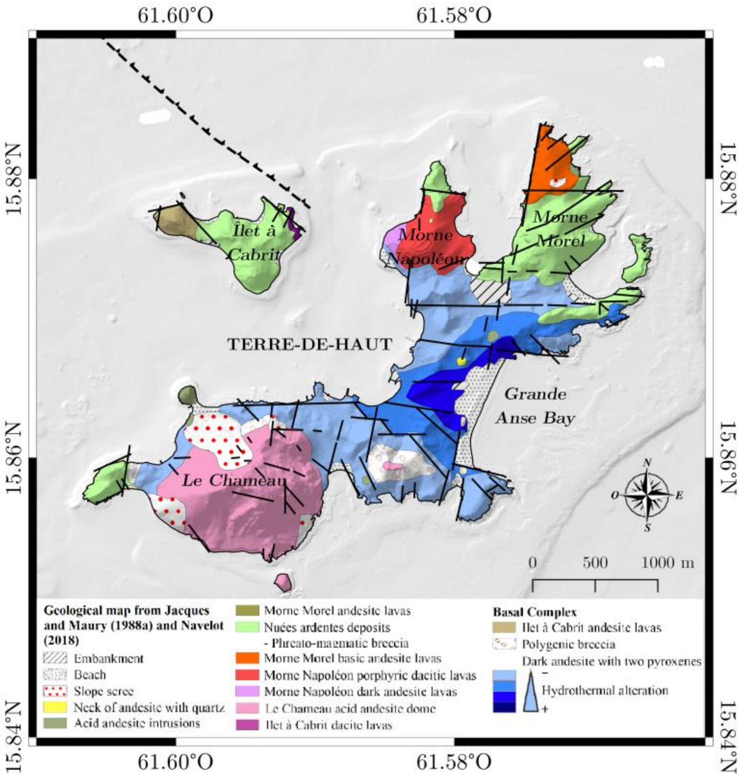

Figure 1: Lithologic map from Jacques and Maury (1988). The onshore fault network is from Verati et al. (2016) and the offshore fault network is from Leclerc et al. (2014). Background shading RGE alti 5 m (IGN).

From a petrographic point of view, the island is composed of products of a medium K calc-alkaline andesitic series (Jacques et al., 1984; Zami et al., 2014). Three volcanic phases between 2.98 ± 0.04 Myr and 2.00 ± 0.03 Myr, built the Terre-de-Haut Island (Jacques et al., 1984; Jacques and Maury, 1988b, 1988a; Zami et al., 2014). Phase I, at 2.98 ± 0.04 Myr (K-Ar age), consists of dacite lava flows and explosive breccia from the Napoléon dome. Phase II, at 2.40 ± 0.04 Myr, built up the Morne Morel, with explosive phreato-magmatic nappes and pyroclastic flows. Phase III, from 2.08 ± 0.03 Myr to 2.00 ± 0.03 Myr, completed the build-up of the island at the Pointe Morel basic andesite flows associated with the phreato-magmatic deposit and the dark andesite lava flow with two pyroxenes in the central part of Terre-de-Haut. This phase ended with several other intrusions, one of the most important is the Chameau dome. The central part of the Terre-de-Haut is affected by high hydrothermal alterations, rocks are totally transformed. Verati et al. (2016) characterized this area as an exhumed geothermal system and described paragenesis associated with hydrothermal alterations.

The hydrothermalized area seems controlled by a set of faults. One of the main questions addressed in this paper is to constrain the extension of the hydrothermalized area at sea.

2.2 Petrophysical input

A large set of samples are collected on the Island and analyzed through different petrophysical techniques (Navelot, 2018; Navelot et al., 2018; Géraud et al., 2020). Among these techniques, the magnetic susceptibility and the remanence are measured.

	Total susceptibility [$\times 10^{-3}$ SI]	Lava flow			Debris flow			Pyroclastics
		Fresh	Slightly to moderately altered	Highly altered	Fresh	Slightly to moderately altered	Highly altered	Fresh
Field susceptibility meter	Average	13.92	13.34	5.99	9.36	13.19	0.94	8.84
	Median	**11.60**	**11.97**	**0.09**	**7.54**	**17.17**	**0.14**	**6.60**
	Min–max	2.06–26.8	3.58–27.62	−0.04–21.47	3.89–24.9	3.96–18.37	−0.17–5.04	4.88–19.33
	n	41	23	7	20	7	7	14
AMS	Average	15.68	12.86	0.02	5.84	5.38	1.57	15.55
	Median	**12.05**	**13.36**	**0.02**	**4.65**	**5.38**	**0.29**	**15.59**
	Min–max	3.54–32.7	0.57–20.91	0.02–0.02	4.19–9.34	5.37–5.4	0.24–4.17	11.15–21.13
	n	157	28	1	5	2	3	9

Table 1: Summary of magnetic susceptibility measurements on outcrops and blocks with handheld susceptibility meter and using AMS (Navelot et al. 2018).

Magnetic susceptibilities are measured on outcrops with a GF Instruments SM-20 or on rock samples with a MFK1-A Kappabridge. This property is measured on a large set of samples representative of the different facies observed on the island (Table 1). Remanence is measured using a MFK1-A Kappabridge. Measurements are done on lava flows only, fresh and hydrothermalized. For the fresh facies, the mean value is 41.97 with a min-max, 0.81-162, highlighting a large variability of the values. For the altered facies, the mean value is 0.0334 with a min-max 0.0021-0.129, the variability is over 2 orders of magnitude. The magnetic signals, susceptibility and remanence, allow to discriminate both facies, with very high values for fresh material and low values for hydrothermalized ones.

2.3 Magnetic data acquisition

In the coastal area near Terre-de-Haut, a high-resolution marine magnetic acquisition was conducted on-board a motorboat, using lightweight electronics and a Bartington MAG-03C fluxgate magnetic sensor. This type of set-up allows for compensation of the magnetic effect of the carrier, in this case the motorboat, using the equations of Olsen et al. (2003) and of the calibration of three-component magnetometers (Munschy and Fleury, 2011).

The magnetic survey covers an area of 18.5 km² acquired in 4 days' time in 2016 (Figure 2.a). The profile spacing is between 50 to 100 m with some irregularities due to navigation difficulties around obstacles. Tie-lines spacing is approximately 500 m. The acquisition is sampled at 25 Hz and the boat has a mean speed of approximately 18 km/h (10 knots), thus giving a data point every 20 cm along profiles. Finally, the navigation uses a GNSS antenna that has a mean positioning error of 5 m that could stand for 10% of the line spacing at worst.

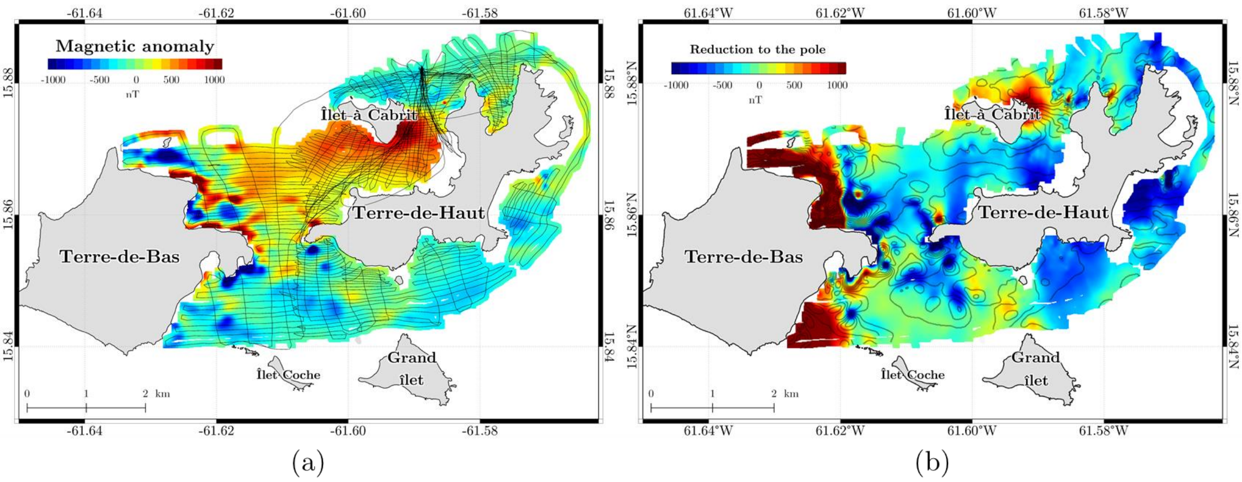

Figure 2: (a) Magnetic anomaly computed from the high-resolution survey around Terre-de-Haut Island. Thin black lines are the motorboat's track lines and the islands are in grey. (b) Reduction to the pole of the magnetic anomaly. Grey lines are the isovalues from the magnetic anomaly, every 150 nT.

Once calibrated and compensated, the dataset is processed to remove the diurnal variation using the absolute measurements from the San Juan (Puerto Rico) magnetic observatory. Using the IGRF12 model (Thébault et al., 2015), the effect of the regional field is removed from the data. Finally, crossing points between profiles and tie-lines were used to correct for levelling effects (Coyle et al., 2014). The remaining standard deviation at crossing points after theses corrections is of 7.2 nT. The navigation uncertainty is mainly responsible for the residual errors in the dataset.

2.4 Interpretation methods for magnetic data

The distance between the survey altitude (sea level) and the magnetized sources varies, and this effect can explain part of the magnetic anomalies. In many cases, it can be considered that the sources are distributed under the bathymetry. However, in this study, the seafloor is formed of several reef terraces that have a thickness of approximately 250 m (Leclerc et al., 2014, 2016). The magnetized sources are buried under the carbonated materials of the terraces that can be considered as non-magnetic. Several magnetic effect models of the bathymetry using different approaches (Parker, 1973) have been led and they support these observations. Therefore, for this study, the location of the magnetized sources being not well understood, they are considered to be evenly distributed on a horizontal layer below bathymetry.

Several approaches can be considered in order to study the magnetization repartition on a horizontal magnetized layer. The most common method for geological interpretation is to use the spectral transform of the reduction to the pole (Blakely, 1995). When considering a horizontal magnetized layer, it is possible to implement spectral inverse filters. Gunn (1975) proposes a transformation that Blakely (1995) later calls the inverse Earth filter. This method consists in isolating the factor responsible for magnetization from the purely geometric factors in the equation of the intensity of the magnetic anomaly caused by a layer of dipoles, in the spectral domain. As the geometric factors are known, it is possible to find the magnetization distribution by a procedure that can be assimilated to a multiplication by an inverse geometric filter (the Earth filter).

The reduction to the pole transform relies on the hypotheses that the magnetization direction is known and that the data plan is horizontal. The inverse filtering methods has the same hypotheses, plus the assumption that the sources are distributed on a plan at a given depth. The volcanic materials onshore Terre-de-Haut Island can be highly magnetized so it cannot be assumed that the direction of the magnetization is like the regional field direction i.e. 38.6° and -14.7° for inclination (I) and declination (D) respectively. Magnetic studies in the Guadeloupe area have shown that it is possible to assimilate the magnetization direction to the one of the Geodetic Axial Dipole: I=30° and D=0° (Carlut et al., 2000; Carlut and Quidelleur, 2000). Since no input on the magnetization direction of materials is available on Terre-de-Haut, the latter direction is used for interpretation.

Figure 3 shows the comparative results of both transformations for a synthetic example considering the discussed directions for the magnetization and regional field directions.

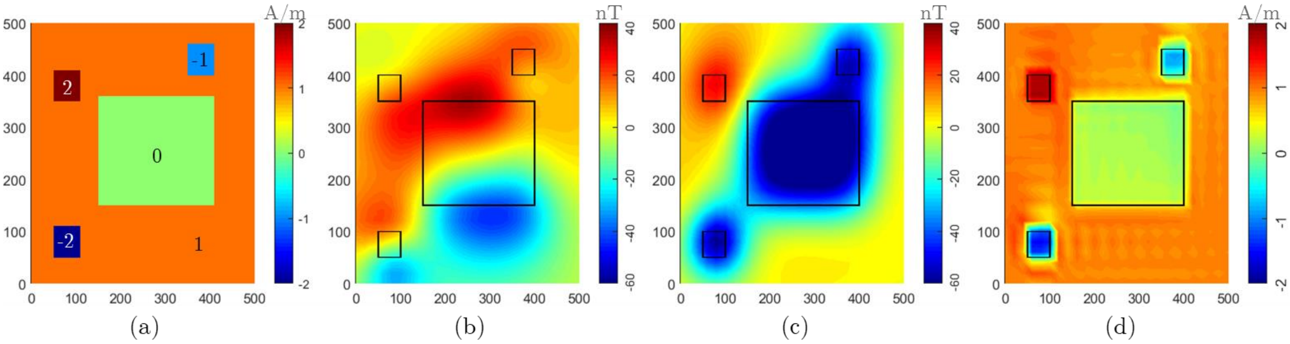

Figure 3: (a) Synthetic model of a magnetized medium with a 1 A/m magnetization intensity. A large demagnetized area in the center has a 0 A/m magnetization. Three minor patches have a magnetization intensity of -2 A/m, -1 A/m and 2 A/m. The negative magnetizations account for a change in the magnetic orientation (normal to inverse). (b) Anomaly of the magnetic intensity caused by the model in (a), 100 m above the sources. (c) Reduction to the pole of (b). (d) Magnetization intensity distribution inferred from Earth filtering of (b).

At this altitude (100 m), the magnetic anomaly generated by the model objects (Figure 3.a) cannot be interpreted without transformation (Figure 3.b). The reduction to the poles shows spread out minima and maxima. The center of the reduced to the pole bodies are consistent with the centers of the modelled bodies except when objects are close together (Figure 3.c). If the hypotheses are met for inverse filtering, the geometry of the model is better recovered with this method (Figure 3.d) than with reduction to the pole analysis. With this method, the magnetization norms can be miscalculated if the inversion depth is not accurate and the result can display high-amplitude low-frequency variations if the grid node spacing is too different compared with the depth.

2.6 Magnetic observations on Terre-de-Haut coasts area

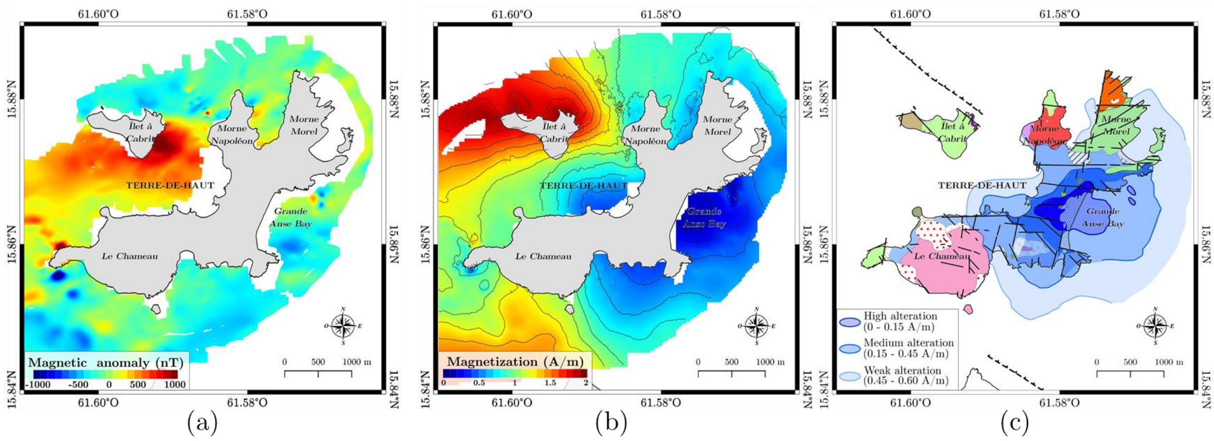

Figure 4: (a) Magnetic anomaly map of the area of interest in Terre-de-Haut, Les Saintes. (b) Inverse filtering of the magnetic anomaly around the Terre-de-Haut Island with the contours every 0.15 A/m. (c) Interpretation of the inverse filtering obtained in (b). The blue polygons are an extrapolation of the onshore altered materials. The geologic map from Jacques and Maury, (1988), Verati et al., (2016) and Navelot, (2018) has the same legend as in Figure 1.

Considering the results of the synthetic case, the inverse filtering in Terre-de-Haut (Figure 4.a) allows for extrapolation of the onshore demagnetized structures (Figure 4.b). This transformation provides a repartition of magnetization on a 1 m thick horizontal layer in A/m. The onshore limits of the polygons are determined using the petrographic map (Figure 4.b). The dark blue area is consistent with highly altered materials onshore and weakest magnetization limits offshore (0 to 0.15 A/m). The lighter blue area is consistent with slightly altered onshore petrographic units and with inversed magnetizations values up to 0.6 A/m. Highly magnetized material can be recognized around the Îlet à Cabrit islet and in the western part of the survey.

3. STUDY OF THE VIEUX-HABITANTS AREA, BASSE-TERRE, GUADELOUPE

3.1 Magnetic data acquisition

Considering the interpretations that were conducted on the Terre-de-Haut exhumed reservoir, a magnetic survey has been carried out in the Vieux-Habitants area. However, the context implies steep topography and a heavy vegetal cover, which requires airborne geophysical surveying. Conventional aeromagnetic acquisition techniques do not allow near-ground surveys in such contexts and a magnetic acquisition survey using a drone was decided. The electronics and fluxgate used for marine acquisition are mounted on a DJI Matrice 100 quadcopter drone. The calibration-compensation process for this set-up is the same than the one described for the marine acquisition.

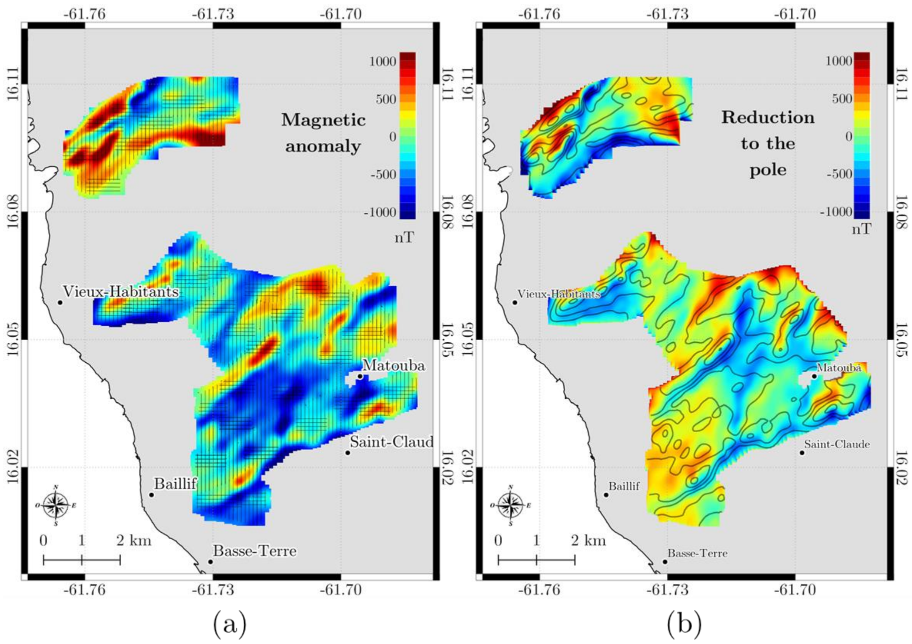

Figure 5: (a) Magnetic anomaly computed from the aeromagnetic survey in the Vieux-Habitants area. Thin black lines are the drone's track lines on profiles and tie-lines. (b) Reduction to the pole of the magnetic anomaly. Grey lines are the isovalues from the magnetic anomaly, every 400 nT.

During a 13-days survey, 34 km² of magnetic data were acquired in 2017. The profile spacing and the acquisition height from the ground are 80 m. Tie-lines are acquired so that each profile is crossed by at least two tie-lines (Figure 5). The acquisition is sampled at 25 Hz and the drone has a mean speed of approximately 29 km/h, thus giving a data point every 30 cm along profiles.

The diurnal correction and the regional field correction are done in the same way as for the marine survey described above. After correction of the levelling effects, the standard deviation at the crossing points is of 11.0 nT.

3.2 Magnetic data interpretation methods

Spectral filtering techniques cannot be applied in this context because the sources are not distributed on a horizontal layer. Strictly speaking, it is not possible to apply spectral transforms like the reduction to the pole because the plan of acquisition is not horizontal. However, first-order interpretations can be achieved through this transform.

In this context, if demagnetization occurs because of the fluid circulation in the fractured reservoir and in damaged zones, it is at depth. Highly magnetized volcanic structures like lava flows are present in the surface and sub-surface. For this reason, the magnetic anomaly caused by a possible demagnetized area is too weak and has a too low wavelength to be identified.

However, at a different scale, localized fault markers in the surface can have a noticeable magnetization either because of alteration or because of the damaged materials in the fault zone. Moreover, reactivated structures can intersect surface lithologies. The displacement of magnetized lithologies can be an indication of a fault trace. For this reason, a magnetic lineament study is conducted using a combination of magnetic map transforms and an automatic lineament picking method (Blakely and Simpson, 1986) (Figure 6.a). The lineaments presented by Figure 6.b are an interpretation of the automatic picking that also include intersecting directions.

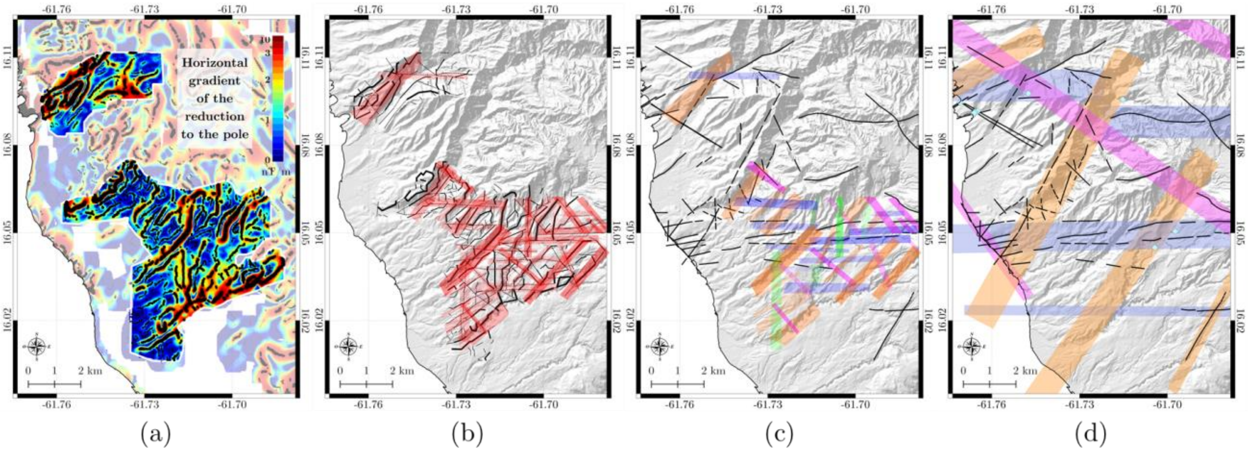

Figure 6: (a) Automatic picking of the maxima on the first order derivative of the reduction to the pole (black dots). The transformed map obtained with the drone are in normal colors, while the pale colors are the results obtained from GUADEM survey (Deparis et al., 2014). The size of each black dot represents the amplitude of the gradient. (b) Solid black lines: automatically picked lineaments from (a). Dotted black lines: interpretation of the automatic picking in terms of lineaments. The main magnetic trends are represented in red. (c) Main magnetic trends obtained from the magnetic study with different colors in function of their orientation, in relation to the onshore fault network (black lines) (Feuillet et al., 2002; Calcagno et al., 2012; Leclerc et al., 2016 and GEOTREF works). (d) Onshore fault network and deformation corridors from the structural synthesis of the GEOTREF project's geological interpretations. The color code is the same as for (c). (b,c,d) Background shading corresponds to the RGE alti 5 m (IGN) digital terrain model.

3.3 Magnetic lineaments interpretation

The directions interpreted from the automatic picking are presented in Figure 6.b and 6.c. They are consistent with the structural directions recognized in the general context of the Guadeloupe archipelago: N10-N160, N50-N70, N90-N110, N120-N140 (Figure 6.d). Part of these lineaments are linked to morphological orientations. Some outlines of surface lithologies are also recognized, mainly when volcanic materials are bordered with pyroclastics or debris flows. Figure 6.d presents the deformation corridors interpreted mainly with geological constraints in this study area. An orientation analysis is led for all results (Figure 7). It is carried out on a larger scale for the geological directions to also include the structures recognized outside the survey area.

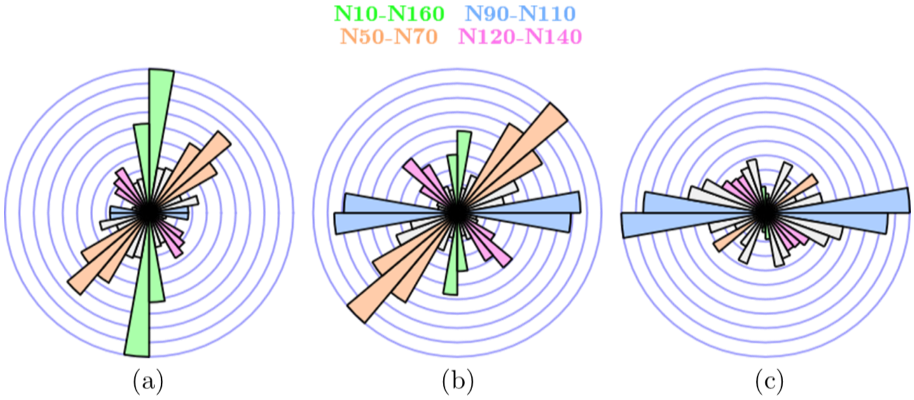

Figure 7: (a) Rose diagrams of the orientations of the lineaments from the automatic picking shown in Figure 6.a, (b) Rose diagrams of the lineaments in Figure 6.b, (c) Rose diagrams of the identified fault network onshore Basse-Terre, southern area.

Some orientations differ in the line orientation diagrams.

- The N90-N110 and N120-N140 are minor in the initial magnetic lineaments (Figure 7.a). These directions mainly intersect other structures (lithologic or tectonic). This infers a consistent displacement that can be interpreted in magnetism, as shown by Figure 7.b. This is consistent with the major E-W directions highlighted by Figure 7.c, that are interpreted as faults (Figure 7.c).

- N50-N70 direction is directly linked to the morphology and to the lithology in this area. Both effects are closely linked because massive lava flows follow an existing topography and create new morphologies. Theses directions are not interpreted as structural directions. However, at a regional level, the Bertrand-Falmouth fault system is oriented as such (Ricci et al., 2015).

- The N160-N10 is deciphered through magnetic lineament study. However, it has not been recovered in the geological structural studies. Theses directions appear mostly in the south-eastern part of Basse-Terre in the structural studies.

The main direction trends obtained with the magnetic interpretation (Figure 6.c) confirm that the regional fault network directions are present at all scales of observation and that this method of lineament detection can supplement the geological field observations when outcrops are scattered and/or of difficult access.

4. CONCLUSION

The inputs from the magnetic interpretation associated with the geological interpretation led to the construction of a conceptual geothermal model for Terre-de-Haut (Figure 8), also presented in Géraud et al. (2020) or Favier et al., (2020).

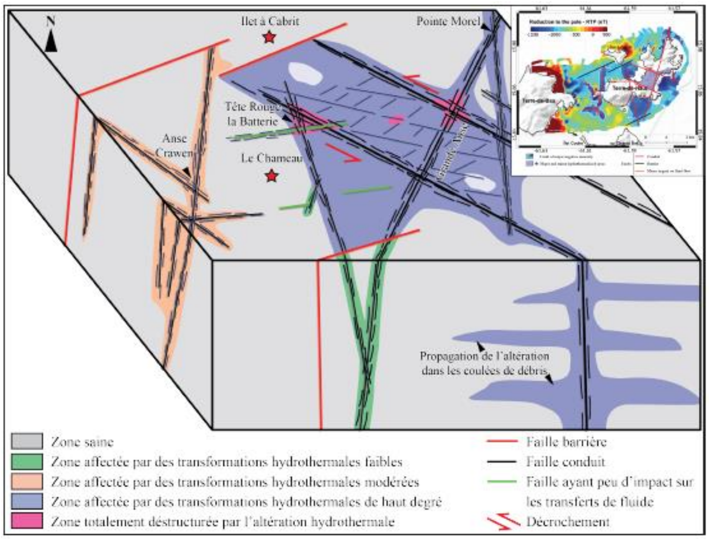

Figure 8: Geological model for the Terre-de-Haut Island.

The magnetic data and interpretation of the exhumed and buried reservoirs are different. For the exhumed reservoir, because the reservoir outcrops and almost no highly magnetized rocks are covering it, the magnetization can be computed. Moreover, the geometry of the area and the acquisition parameters allow to make the right hypotheses to use spectral domain inverse filters. The buried reservoir appears to be too deep under magnetized volcanic material to be directly interpreted. The flight altitudes of the drone and the topography of the island do not allow for the same interpretations techniques as for Terre-de-Haut. However magnetic lineament analysis provides constraints for the geological interpretation. A conceptual model of the reservoir underneath the Vieux-Habitants-Soufrière area has been proposed in Navelot (2018) solely based on geological studies. Possible deformation corridors can be interpreted in magnetism. They are important to understand the reservoir because it has an important tectonic control of this reservoir (Bouchot et al., 2010; Navelot, 2018).

Modeling techniques could bring constraints for buried reservoirs. However, an oversimplified model like the one of Terre-de-Haut will not fit for this context. It will be necessary to consider the flight altitudes of the drone, the steep topography of the island and the magnetization of the different surface lithologies. This kind of magnetic interpretation cannot be carried out in the spectral domain because the magnetic data are not lying on a horizontal plane.

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