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Geophysical Methods Applied to the Assessment of the Bouillante Geothermal Field (Guadeloupe, French West Indies)

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ABSTRACT

The geothermal field of Bouillante is located on the west coast of the Island of Guadeloupe in the Lesser Antilles. It has been explored in the beginning of the 70's and was producing 4 MWe until 2003 from a single well, BO2. Production increased up to 15 MWe in 2004, with two new wells, BO5 and BO6, drilled 500 m south-east of BO2. The producing zone is located along the EW Cocagne Fault, intersected by these three wells at different depths between 300 and 1000 m. Production and tracer tests and geochemical results show that the reservoir is of large extension and connected to the sea. Geological reconnaissance and the existence of hydrothermal springs along the seashore and off shore in the Bay of Bouillante suggest that other geothermal resources possibly exist in the northern part of the bay.

Different geophysical methods have been applied in 2001, 2003 and 2004 in order 1) to constrain the conceptual model of the known geothermal field and 2) to locate this hypothetical reservoir: 2-D electrical imaging survey, bathymetry mapping, off shore high resolution seismics, off shore and on shore magnetic survey. Geological, thermal and production data from existing wells have been used to constrain geophysical interpretation. Electric imaging has been performed using a dipole-dipole array along an 6-km long profile, parallel to the coast. The interpretation outlines faults and conductive zones which are interpreted as either productive or intensely hydrothermally altered zones. High resolution marine seismic data have been acquired along the shore with a 6-channel streamer and a 1000 J sparker source. Faults are pointed out and related to faults mapped inland. The offshore magnetic survey detects anomalies which correlates, from one part, with those faults and, on the other part, with volcanic cones that appear on the bathymetric map of the bay. Magnetic measurements inland help to link the structures detected offshore to the geological structures inland.

1. INTRODUCTION

The geothermal area of Bouillante is located on the west coast of Basse-Terre, the western part of the Island of Guadeloupe (Lesser Antilles). Its high temperature geothermal potential is largely controlled by the volcanic and structural conditions of the Guadeloupe island (Fig. 1). The latter is part of the Lesser Antilles volcanic arc, linked to the subduction of the North American plate beneath the Caribbean one. The Bouillante area is characterized by a recent volcanic history (from 2.5 to 0.6 My) and is located at the intersection between two fault systems: a terrestrial E-W graben system clearly evidenced by a structural field study (Feuillet et al., 2002) and a submarine NW-SE fault scarp evidenced by bathymetric data (Traineau et al., 1997).

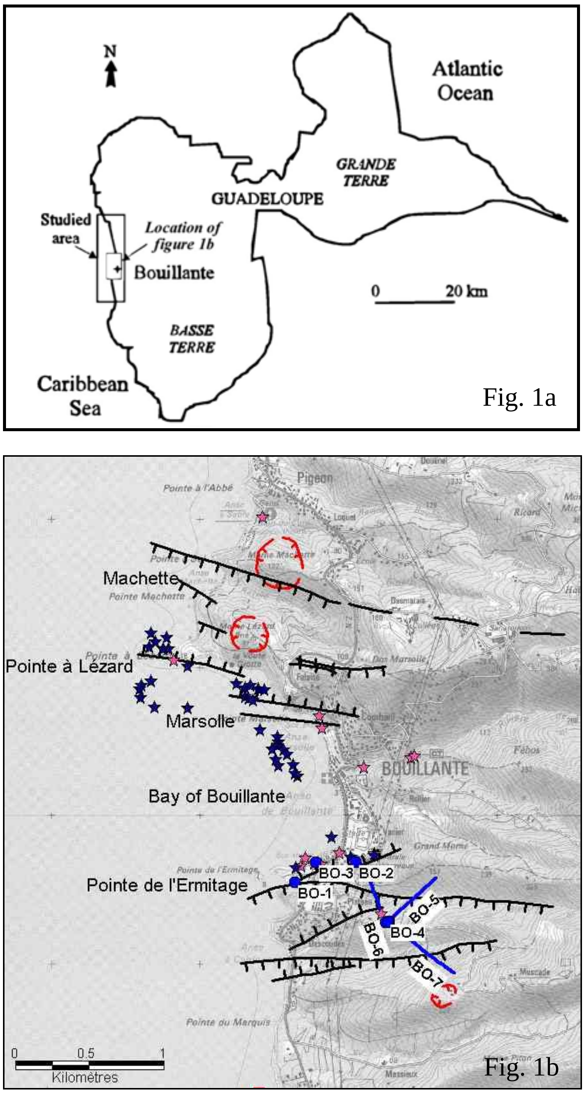

Figure 1: a) location of the geothermal field of Bouillante. b) structural map of inland faults. Stars indicate hydrothermal manifestations. BO1 to BO7 and blue lines are geothermal wells.

The exploration of the field started in 1973 when four wells, BO1 to BO4 (Fig. 1), were drilled, based on hydrothermal surface manifestations, geology, temperature gradient in shallow wells, geochemistry and geophysics (electromagnetic and a seismic reflection profile). The BO2 well found a geothermal resource at 320 m depth, with a temperature of 248 ° C and a total production of 120 t/h of water, among which 20-25 t/h of steam. This well was connected to a 5 MWe power plant, which has been working since 1988 to present, supplying up to 3 % of the Guadeloupe electrical consumption. In the BO4 well, a maximum temperature of 253 °C and a production rate of about 50 t/h of water and 10 t/h of steam were measured in the 70's. Investigations started again in the 1990's and the production rate of BO4 increased by 50 % by thermal stimulation (Tulinius et al., 2000). New geological studies, tracers tests and brine analysis (Sanjuan et al. 2001) indicated that BO2 and BO4 are connected through the EW faults system to a large reservoir, with a composition of brine of 40 % seawater and 60 % meteoric waters. It was then decided in 1999 to drill 3 new directional wells: BO5 and BO6 toward NE and NW respectively and BO7 toward SE. The objectives were to intersect: 1) this fault system and 2) the areas of low resistivity recognized by magnetotellurics and electrical methods in the 80's. BO5 and BO6 wells resulted to be good producers, with temperatures between 250 °C and 260 °C. Meanwhile BO7, despite temperatures larger than 240° C, was dry and has no permeability. Considering that, a new power plant of 10 MWe capacity has been built and production would now increase up to 15 MWe, using the production of BO5 and BO6 wells.

New investigations have been carried out simultaneously in order 1) to constrain the conceptual model of the known geothermal field and 2) to evaluate the geothermal resources in the northern part of the Bay of Bouillante. In fact, thermal springs on the northern coast line and on the sea floor of the bay indicate that high temperatures fluids are leaking from an hypothetical reservoir located either beneath the bay or close to the EW faults located north of the known reservoir. Different geophysical methods have been applied at the end of 2003 and 2004 around the Bouillante geothermal field: off shore, high resolution reflection seismic, magnetic and bathymetric surveys and, onshore, 2-D electrical imaging and a magnetic survey. This paper is mainly devoted to describe and analyze the geophysical results.

2. GEOPHYCICAL DATA ACQUISITION AND PROCESSING

2.1 High resolution seismic survey

A high resolution marine seismic survey has been carried out in November 2003, with a 6-channel streamer and a 500 J to 1000 J sparker source. A total length of 325 km of seismic profiles have been recorded from 16.1° N towards 16.22° N. Depths to sea bottom exceeded 40 m in order to avoid multiples. An example of a seismic profile is showed in figure 4. Vertical resolution is 4 m, corresponding to a two-way travel time of 5 ms. The profile has been migrated with a constant velocity of 1600 m/s. Maximum depth of penetration is 300 m. An uplift of the acoustic basement can be observed on the seismic profile (shots 1200 to 1500), limited to the west by a N170 normal fault, which underlines the continental shelf break, and to the northeast by a small asymmetric extensional sedimentary basin. This high basement is a major characteristic and it is located in front of Pointe à Lézard, i.e. the northern limit of the Bay of Bouillante.

Figure 2 shows the structural interpretation of the seismic data. Three families of faults are observed: 1) normal faults of direction N150 to N180 dipping mainly toward W; 2) normal faults of direction N20 dipping toward E; and 3) normal faults of direction EW dipping either toward north or south. The alignment of N170 faults is another major feature, limiting the continental shelf toward the west. The N140 structures may be linked to the Montserrat-Soufriere volcanic lane. Surprisingly, there is almost no continuity between the inland faults, mainly EW, and the fault detected by the offshore seismics. One reason could be that the latter NNW-SSW trending faults are developed within old basement formations which are covered by recent volcanic and detritical products outcropping around the Bay. Nevertheless, important EW features are outlined on the sea bottom topography (Fig. 2), in particular in front of the Bay of Bouillante. One of them is the continuation westward of the inland faults of Marsolle and Pointe à Lézard,. This difference of faulting directions between inland and offshore is one of the clues of the complexity of the geological structure of the Bouillante area, as already noticed by many authors (Bouysse et al., 1990, Feuillet et al., 2002).

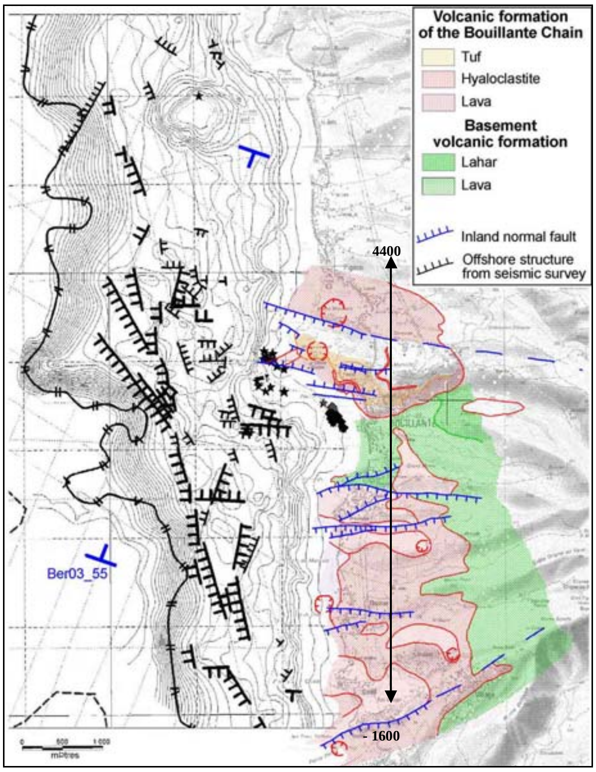

Figure 2: Geological map of Bouillante area. Structures offshore have been defined by seismics. Blue ⊥ signs indicate seismic profile Ber03-55 and its start on figure 4. Dipole-dipole section is shown by a double-arrow line.

2.2 Electrical resistivity imaging

A dipole-dipole array of 6 km length, has been measured along a NS direction, at a distance from the coastline varying from 200 m to 1500 m. Lengths of dipoles were respectively 200 and 400, with n = up to 5. The maximum depth of penetration, 700 m, has been reached from 1 km south of the known geothermal field to 1.5 km north of the town of Bouillante. Data have been interpreted and inverted with RES2DINV (Geotomo software, 2001), which takes into account the topography and yields a 2-D resistivity profile (Fig. 5). The effect of the sea has not been taken into account, but it will be estimated by a complementary dipole-dipole survey using a equatorial array configuration. Resistivities are generally lower than 30 ohm.m, except in the northern part of the Bay of Bouillante. Several conductive features can be related to the known producing zones.

2.3 Magnetic survey

Offshore magnetic data have been recorded simultaneously with the seismic reflection survey data, using a submarine MNR magnetometer (Truffert et al., 2004). Additional lines of survey have been performed in the Bay of Bouillante, where water thickness is less than 40 m, in order to get data closer to the coast line and to allow merging with the onshore measurements. Inland, magnetic data have been acquired simultaneously with the dipole-dipole survey. Important anomalies are observed on the map of the vertical gradient reduced to the pole (Fig. 6). There is a good continuity of the offshore and onshore anomalies, which its origin could be associated mainly with lava flows or volcanic edifices.

3. INTERPRETATION

3.1 Geological data

Due to the bad outcrop conditions related to the existence of the tropical vegetation and high elevation, the field study have been mainly concentrated along the coast where the volcanic and volcano-clastic formations are better exposed. The bedrock in the vicinity of the geothermal power plant consists of submarine to terrestrial volcanic rocks of original low porosity (Traineau et al., 1997). From the recent production boreholes (BO5, BO6, BO7), the deep seated geology could be summarized as follow from the top to the bottom: a first sequence made of volcano-clastic formations related to the aerial erosion of the Bouillante hills, then massive flow lavas, then brecciated formations embedded within massive flow lavas and finally a thick tuff formation highly hydrothermally altered.

On the field, fracture analysis reveals several types of structures: dikes or intrusions, small-scale joints, mineralized fractures, open fractures and normal faults. The dominant fracture set is oriented mainly N100 to N120E with high dipping values. The normal faults, which are located outside the Bay of Bouillante, are mainly faults characterized by the lack of hydrothermal filling. On the contrary, the fault zones which are located in the vicinity of the geothermal boreholes or close to the hydrothermal manifestations (altered ground, steaming ground zones, thermal springs) show a more complex pattern. They show fracture concentration, are hydrothermally altered and filled by mineral products. The deviated production boreholes BO5 and BO6 cross-cut deep permeable zones interpreted as the trace of the so-called Cocagne Fault (Fig. 3). This normal fault, strongly dipping and WNW-ESE trending, seems to act as a outflow zone of high permeability.

.Based on rock samples collected on surface and at various depths within the recent boreholes drilled at Bouillante, several hydrothermal mineral associations were delineated (Patrier et al., 2003). On surface, the main hydrothermal clay assemblages are dioctahedral smectite and ordered illite-smectite mixed layers. A close spatial relationship was outlined between zones of present-day surface hydrothermal manifestations and the occurrence of smectites. The ordered illite-smectites are mainly associated with brecciated pebbles collected on the beach. They are interpreted as epithermal breccias, indicators of a neighboring geothermal reservoir. From cutting samples collected within the production boreholes, a broad vertical evolution can be outlined versus depth: a superficial dioctahedral smectite zone, deeper an illite-smectite to illite zone and then a deep chlorite zone (Fig. 3).

3.2 Geophysical data

The geophysical surveys have been designed to cover the whole Bay of Bouillante, in order to gauge the methods on the known resource and to explore the north of the Bay. Inland, magnetic and electrical imaging data give us information about the main faults that control the geothermal field at the south of the Bay: i.e. Descoudes, Plateau, and Cocagne faults.

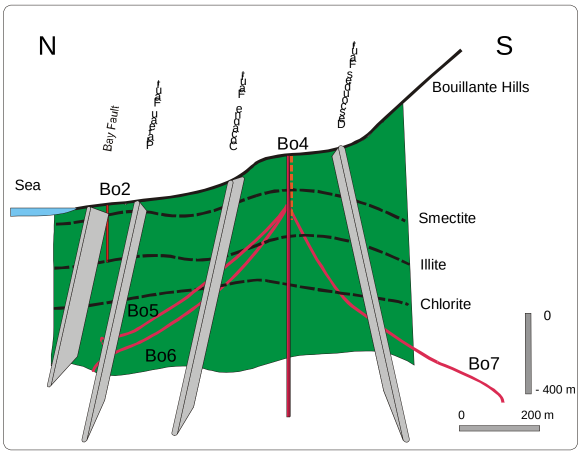

Figure 3: Schematic vertical distribution of the clay minerals projected on a N-S cross-section. Vertical and directional wells are plotted in black and red, respectively. The main faults deduced from borehole data are plotted in Grey. Vertical scale is twice the horizontal scale.

At the north of Bouillante town, the orientation of magnetic anomalies varies from NNW-SSE to E-W (Fig. 6), which correlates either with the alignments observed on the bathymetric map of the bay, or with the main EW direction of the faults of Marsolle and Machette. That suggests that the potential geothermal resource in the north of the Bay could be controlled by a structural context more complex than for the presently known geothermal field.

Offshore, the main magnetic anomalies define two kind of alignments separated by a clear N160-170 axe (dotted line in figure 6a) : 1) oriented N40-N60 towards east of this line ; 2) oriented N80-to EW towards west. It is worth noting that this axe is parallel to the steep fall off the continental shelf observed on the bathymetry at ca. 2.5 km from the coast. Depths of anomalies estimated by Euler deconvolution show that the sources of these anomalies are not deeper than 200 m towards the east, meanwhile depths are larger than 800 m towards the west. This is coherent with the deepening of the seismic basement westwards observed by reflection seismic (Fig. 4). In both case, magnetic bodies are deeper than sea bottom. Inland, there is a good correspondence between the known volcanic edifices and positive magnetic anomaly : at Pointe à Lézard, Morne Piton, Pointe de l'Hermitage etc. In the latter case, the continuation of this anomaly in the sea is obvious, underlining the system of EW faults where the geothermal field is located. Finally, it is worth noting the division of the Bay of Bouillante in two domains along an N30-N40 line (Fig. 6b). In the western part, the amplitude of the magnetic field is relatively high corresponding to shallow volcanic intrusions, meanwhile towards east the magnetic field is quite low. We suggest that the cause could be an effect of demagnetization in this area, either by thermal effect or by hydrothermal alteration. The Curie temperatures of magnetite and pyrrhotine, respectively 580 °C and 320 °C, are higher than the temperatures measured in the Bouillante boreholes and such sources are unlikely located at shallow depth. Consequently, the thermal effect could be responsible only for the low frequency part of the anomaly, coupled with the probably dominant effect of the many hydrothermal manifestations in the northern part of the Bay, inland and at the sea bottom. This effect has already be noticed in other geothermal fields, e.g. Wairakei in New Zealand (Allis, 1990). The N30-N40 oriented limit between both areas could be correlated with a « valley » of same direction observed in the bathymetry of the Bay. Several cones of unidentified origin (volcanic, coral reefs ?) are aligned along this valley. Southwest of Pointe de l'Ermitage, the seismic reflection survey has detected two conjugate faults in the same direction (Fig. 2), forming a small extensional basin.

In the southern part of the resistivity imaging profile (Fig. 5), conductors and resistors can be linked either to the geological structures or to the information from the wells and the analysis of clay minerals distribution with depth (Fig. 3). As an example, the resistor R2 mimics the horst shape on the top of which the drilling platform of BO4 is located, according to geology. Moreover, according to Anderson et al. (2000), the transition from smectite and smectite-illite assemblages to chlorite induces an increase in the electrical resistivities. That means that the transition from the caprock to the reservoir could be characterized by a transition from the conductive smectite and illite-smectite clays to the more resistive chlorite ones. In the case of the wells BO5 to BO7, the transition between the different clays assemblage seem to be more or less monotonous (Fig. 3), corresponding more or less to a vertical succession of shallow conductors and deep resistors (e.g. R2) between Descoudes and Plateau faults. Nevertheless, two conductors deepen around the resistor R2 from the surface down to 700 m. The vertical projection of the unproductive well B07 intersects the resistor R2 (resistivity > 50 ohm.m), meanwhile the productive wells BO5 and BO6 intersect first a conductor and then enter in an area of slightly higher resistivity (5-10 ohm.m). Then, it seems that if the increase of resistivity is noticeable in the geothermal reservoir, the lack of permeability induces a larger increase of resistivities around well BO7. Up to now, we cannot conclude respect to the significance of conductor C3, except the fact that it has been already detected by former MT studies (Puvilland, 1986). In the northern part of the profile, the distribution of resistivities is quite different. A clear separation appears between the shallow resistive layers (R1) and the deep conductors C1 and C2. There is also an important electrical limit between C1 and C2, which could be associated to Marsolle fault and to the south limit of a magnetic anomaly elongated parallel to the coastline (Fig. 6b). The existence of a conductive layer beneath a resistive one could be interpreted as a thick lava flow of very low porosity, overlying hydrothermally altered layers.

Regarding the offshore high reflection seismic survey, the link between the defined structures and those recognized inland has to be interpreted within the more general framework of the regional tectonics. The complex N160-N170 faulting could correspond to the southern end of the regional normal fault with left lateral slip component which runs from Montserrat Island to Basse-Terre (Feuillet et al., 2002). As discussed earlier, the NNW-SSE trending faults are not observed inland. Nevertheless, we suggest that they are developed within the basement formations and are hidden by the recent volcanic and detritical products. Then, in the Bouillante area, this NNW-SSE fault system could intersect the western end of the system of EW to N100 normal faults which are the northern limit of the EW graben structure in which the active volcano of La Soufriere is located. This graben crosses the south of Basse Terre and is the prolongation inland of the Marie Galante rift. These EW normal faults and graben correspond to a regional NS extension, parallel to the trench, which is the result of stress partitioning of the NE-SW subduction with the left lateral slip along the N160-N170 Montserrat-Basse-Terre fault (Feuillet et al., 2002). From the geothermal point of view, it is important to notice that the maximum tensional stress will be concentrated at the intersection of both system of faults. The small tensional basin located offshore at the north of Pointe à Lézard is an example of this kind of intersection. Consequently, one clue for future geothermal exploration could be directional drilling towards areas where both directions of fractures have been recognized, either by seismic or in sea floor topography.

4. CONCLUSION

New geophysical data have been acquired in the area of the geothermal field of Bouillante, aiming at to constrain the conceptual model of the present resource and to give insights in the extension of the field towards the north. High resolution reflection seismic, bathymetric and magnetic surveys offshore and inland magnetic and 2-D electrical resistivity imaging surveys have been carried out. The offshore data confirm the difference of geological structural regime between offshore and inland. That corresponds to the intersection of the Montserrat-Basse-Terre fault with the EW normal fault system of Bouillante. This is now well explained within the framework of the regional tectonics and has implications in the understanding of the fracturation. Integration of offshore and inland magnetic data has pointed out important anomalies that can be related to the structural geology but also to the effect of hydrothermal alterations. The 2-D electrical resistivity imaging brings noticeable correlations between resistivity and the appearance of different types of clays minerals as a function of temperature.

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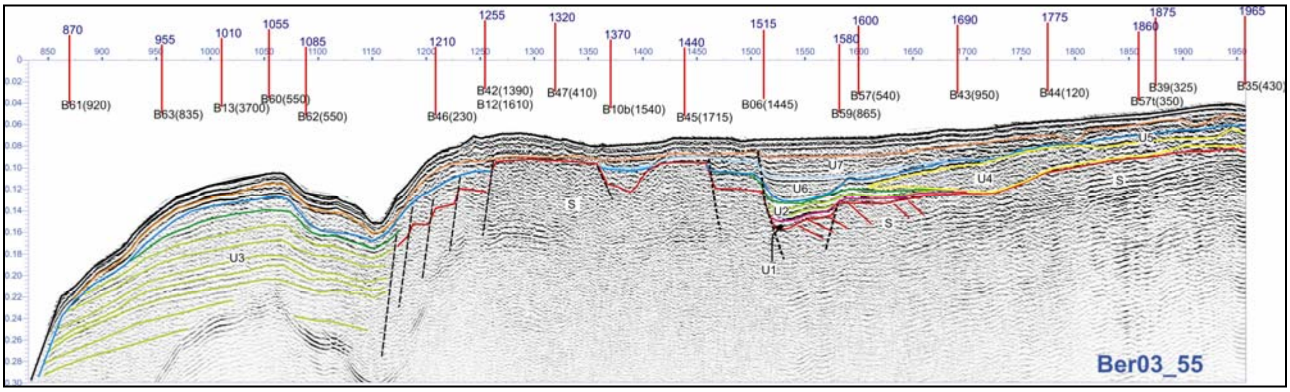

Figure 4: SW-NE seismic profile BER03_55 migrated with a constant velocity (v=1600m/s), crosscutting the continental plateau at the West of the Guadeloupe Island (see location in figure 2). U1 to U7 are different seismic units and S the seismic basement. Horizontal scale is in m, vertical scale in s (TWT).

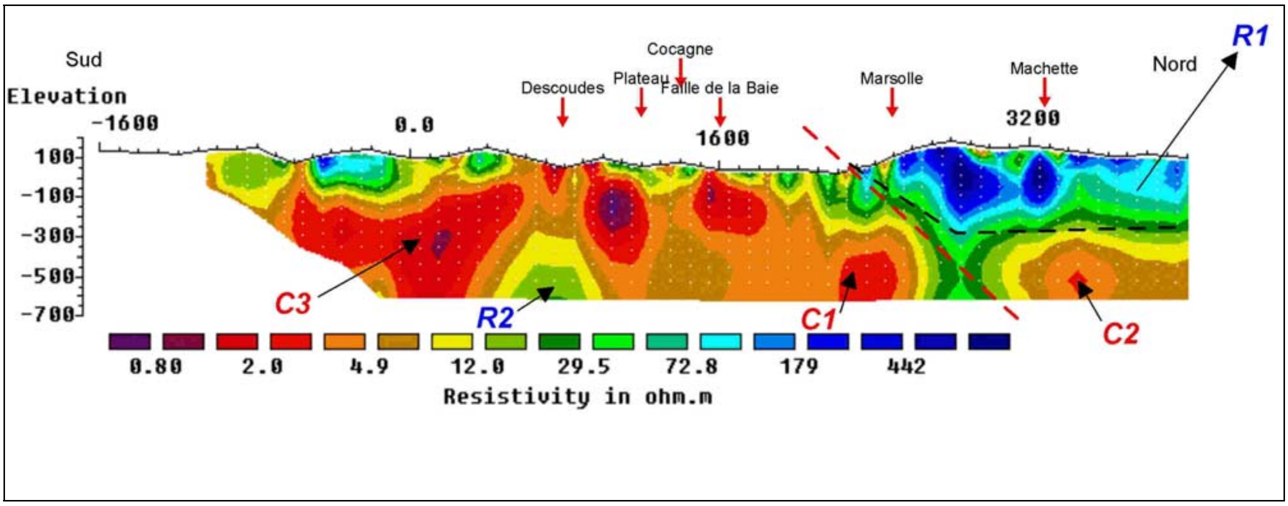

Figure 5: Resistivity model for the NS dipole-dipole profile. Cn are conductors and Rn resistors. Dotted lines indicate electrical limits. Horizontal scale along the profile is in m.

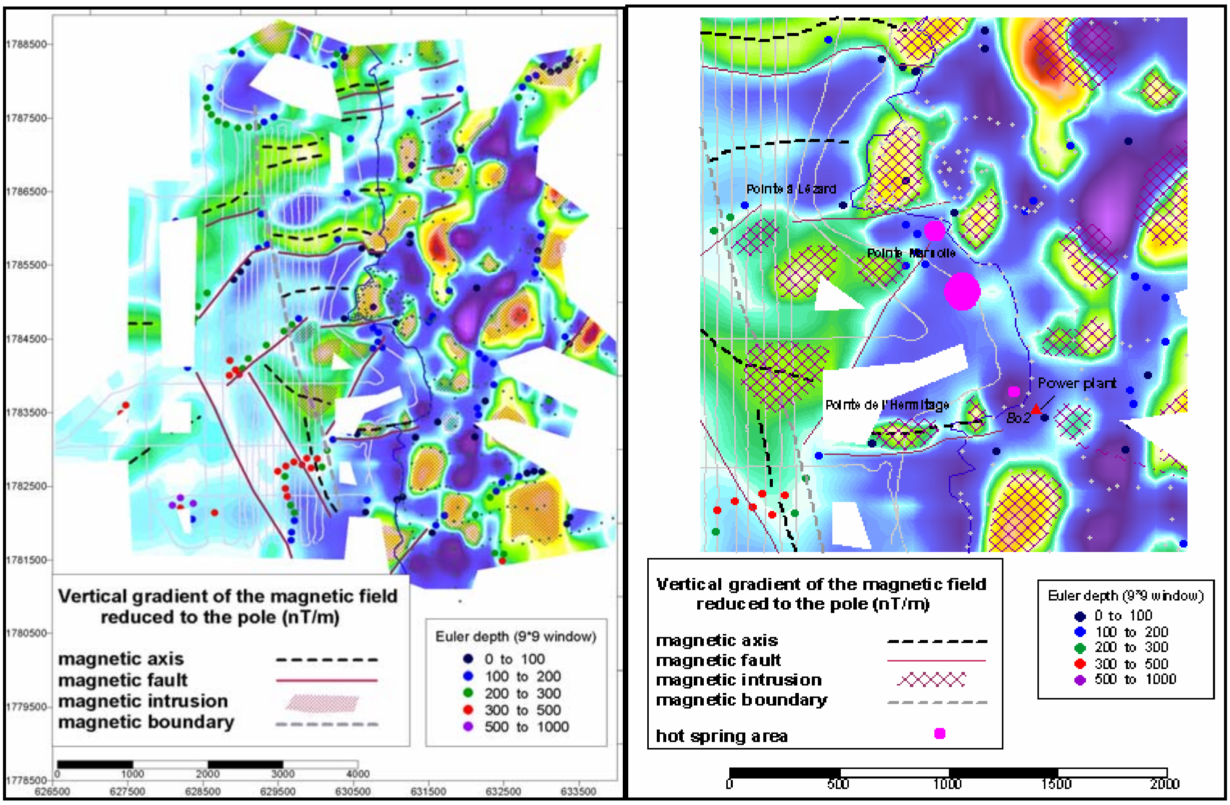

Figure 6: Vertical gradient of the magnetic field reduced to the pole with upward continuation to 100 m. Green lines indicate survey profiles offshore, crosses are the measurements points inland.