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Airborne and land-based electromagnetic (CSEM and MT) surveying for geothermal exploration in the Martinique island

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ABSTRACT

Exploring for geothermal resources using land-based electromagnetic methods can be very challenging due to the presence of strong human-generated and “geological” noise. In such context, some passive EM techniques like the Magneto-Telluric method may not be applicable at all and a dedicated toolbox of EM techniques capable of dealing with these issues is required. In this paper, we will focus on the challenges encountered while exploring for geothermal resources in volcanic islands, namely a highly heterogeneous near-surface creating strong static-shifts, the presence of a sea/land transition zone and a high degree of urbanization over the area of interest. We will show that the combination of airborne with land-based controlled-source EM (CSEM) and MT surveying provide a robust approach and illustrate these aspects with two EM datasets acquired over the Martinique Island, in the French Lesser Antilles.

The first study extends over the Lamentin bay area located near Fort de France, the main city of the Martinique Island. Here, exploratory drilling since the 1980's highlighted a polyphased hydrothermal system with fossilized hydrothermal features and a recent hydrothermal activity. The geothermal system is poorly understood and has prevented any exploitation of the geothermal resource to date. In an attempt to reduce the geological risk for future geothermal development, a joint 3D airborne and CSEM survey was performed. Here, the presence of anthropic EM noise made MT data hardly usable. Processing and inversion of the EM dataset allowed to map the geometry of the hydrothermal alteration “caprock” as well as underlying volcanic substratum and potential geothermal reservoir.

The second study extends over the Petite-Anse area located in the South-West of the Martinique island. Here, evidences for high-temperature geothermal system ($>200^{\circ}\text{C}$) are present and the design of exploratory boreholes requires to map accurately the geometry of the “caprock” and potential geothermal reservoir. To do so, a high-resolution 3D CSEM and MT survey was conducted in Spring 2019. Similarly to the Lamentin area, MT data suffered from strong cultural noise. CSEM data quality is sufficiently good to map the extent of the area of geothermal interest and areas to avoid drilling into (e.g. dykes).

1. INTRODUCTION

Land-based electromagnetic (EM) methods, attempting to detect contrasts in electrical resistivity between target resources and their surroundings, have been developed and utilized for exploring buried resources such as minerals, hydrocarbons, geothermal energy, or groundwater for more than a century (Streich, 2016 and reference therein). Dealing with noise has complicated EM recordings ever since the first EM measurements were made. Various types of noise have been recognized as, for instance, human-generated noise (e.g. power grid, railways, industrial facilities). Magnetotelluric signal can be regarded as noise in the context of active EM surveying. Finally, subsurface heterogeneity like bodies at depth, small-scale structure near the sources or receivers not resolvable by the measurement technique used, can mask target responses and hence be considered as “geological noise”.

In order to explore for underground resources in a large variety types of environments (e.g. urbanized areas, mountainous terrains, volcanic areas, sedimentary basins), we have developed a comprehensive toolbox of EM techniques capable of dealing with such challenging EM environments. In this paper, we will focus on the challenges encountered while exploring for geothermal resources in volcanic islands, namely a highly heterogeneous near-surface, the presence of seawater and a high urbanization over the areas of interest. We will show that combined airborne and land-based controlled-source EM methods provide a robust approach and illustrate these aspects with an EM dataset acquired over the Martinique Island, in the French Lesser Antilles.

2. LAMENTIN BAY AREA

2.1 EM survey objective

The study area is the Lamentin bay area located near Fort de France, the main city of the Martinique Island (Lesser Antilles, France, see figure 1). This area is an alluvial plain lying over a volcanic substratum with a strong hydrothermal activity as evidenced by numerous hot springs. Exploratory drilling since the 1980's highlighted a polyphased hydrothermal system with fossilized hydrothermal features and a recent hydrothermal activity. In terms of hydrogeology, the area is characterized by a superficial free aquifer in the sediments subject to seawater infiltration. As a result, the geothermal system is poorly understood and has prevented any exploitation of the geothermal resource to date.

In an attempt to reduce the geological risk for future geothermal development, BRGM was mandated to conduct a geophysical survey over the area. It however exhibits all the typical challenges that can face geophysical methods in such volcanic islands. First, the near-surface is a highly heterogeneous system with a mix of altered and unaltered lavas alternating with volcano-detritic sediments. Secondly, the area is entirely urbanized and therefore the use of Magneto-Telluric soundings for deep EM imaging is not possible.

Finally, the geothermal field is likely to extend underneath the bay area and the acquisition of offshore data is necessary. In order to tackle these issues, our strategy was to acquire high density airborne EM data to characterize the shallow layers and combined them with onshore/offshore CSEM data for deeper imaging.



Figure 1: Location of the CSEM recording stations (black dots) and CSEM transmitter (thick red line) acquired of the prospective area of the Lamentin Bay area, next to the Fort de France city. The geothermal field is likely to sit underneath the bay area where several exploratory wells have been drilled (red circles).

2.2 Airborne EM survey results

A heliborne EM survey covering the whole Martinique has been carried out using the SkyTEM system, which operates in a dual transmitter mode. The survey was flown primarily in the N-S direction with a 400 m framework, locally reduced to 200 to 100 m spacing. The spacing between each EM sounding along the flight lines is approximately 30 m. The nominal height of the loop was on average about 64 m above ground level, due to the variable topography of the island.

Because of the presence of many urbanized areas and strong power lines that drastically deteriorate EM responses, the area of interest was only partially covered and particular attention was paid to properly remove noise from the data at the processing stage. The airborne EM soundings are available every 10m along flight lines. Data were then inverted using the Spatially Constrained Inversion (Viezzoli et al., 2008). Each EM sounding was inverted to obtain a 1-D earth model constrained vertically and laterally by nearby soundings.

Figure 2 shows resistivity maps recovered at 5m, 25m, 100m and 200m depth over the area of interest. It clearly delineates a shallow conductive anomaly ($< 1 \Omega.m$, $< 25m$) around the bay area representative of the seawater intrusion zone. On the other hand, the eastern part of the survey is highly resistive at all depth ($> 100 \Omega.m$) highlighting the presence of thick andesitic lavas.

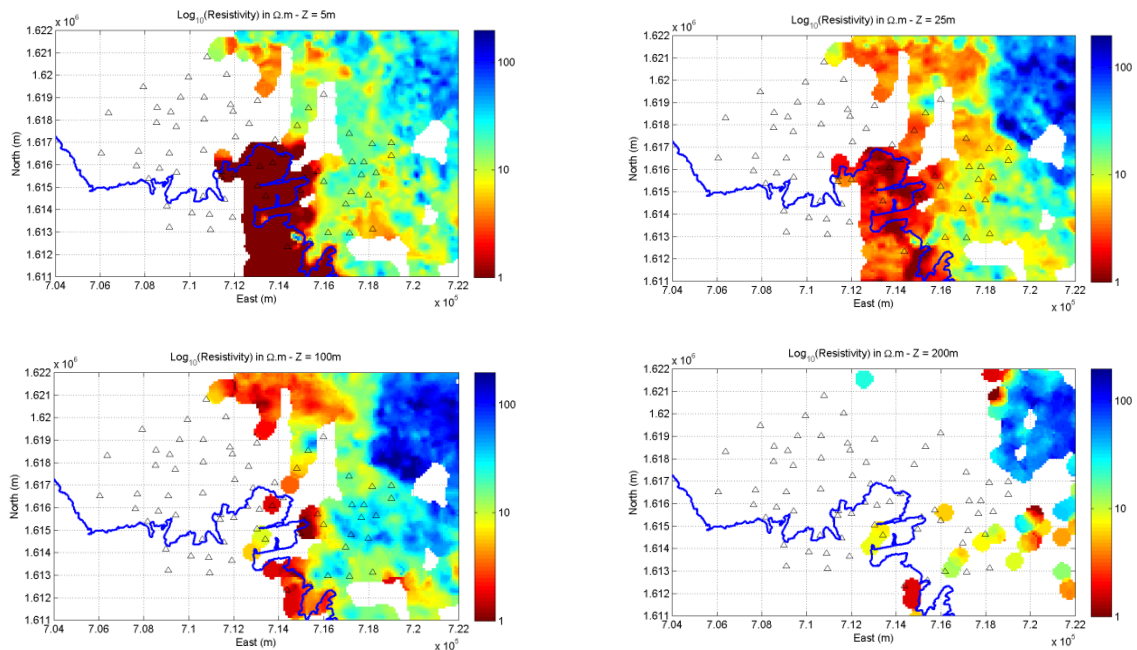


Figure 2: Resistivity maps recovered at 25m, 100m, 250m and 1000m depth from the 1D modelling/inversion of the airborne EM and CSEM datasets. Black triangles represent the CSEM recording stations.

2.3 Land/shallow marine CSEM survey results

a) CSEM data acquisition and processing

The CSEM survey was acquired using a double LEMAM injection setup for the transmitter (LEMAM standing for Long Electrode Mise-à-la Masse). It uses the metallic casings of boreholes as long electrodes for current injection. Here, two deep exploratory boreholes (~400m) connected with a 4km long electric cable were used. Due to the good electrical coupling of the casings with the earth, the current injected was about 30A. To adequately characterize the subsurface, a broad band of CSEM frequencies (fundamental frequencies from 0.125 Hz up to 512 Hz increasing with a factor 4) was acquired with a minimum of 150 cycles at low-frequencies to ensure proper stacking of any random noise. The waveform was a square wave to ensure powerful harmonics to be measured as well. A total number of 100 CSEM recording stations were deployed on the Lamentin bay area (figure 1), 80 onshore and 20 offshore. They were Metronix ADU06 or ADU07 acquisition systems, MFS07 or MFS06 magnetic coils and 2 orthogonal electric dipoles from 20 to 100m long.

Raw data have been processed in the frequency domain using a proprietary code. After automatic and manual quality control of the processed data, 20% of the data was rejected due to high levels of noise, mainly due to the weak CSEM signal at stations at large distances from the transmitter (> 6km). The remaining 80% of the data were considered of good quality and subsequently inverted. In total, 42 frequencies (= fundamental frequencies + frequencies up to the 13th harmonics x 7 transmitter frequencies) have been processed to provide a broadband signal and allow an easy removal of noisy frequencies bands (e.g. industrial noise at 50Hz and harmonics). At this stage, we only worked with the amplitude and phase of the maximum axis of the polarization ellipses of the horizontal electric field as their spectra are a lot smoother and hence easier to quality control than individual horizontal components (which can sometimes cross zero and hence be confused with noise). It surely comes at the expense of losing some information, especially the “3D effects”, but we consider these as second order effects that will be studied at a later stage.

b) CSEM static-shift corrections

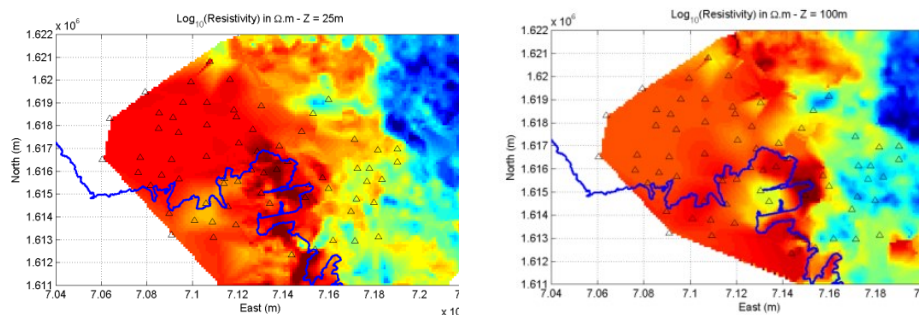
As evidenced by the airborne EM data (figure 2), the near-surface (<100m) can be very heterogeneous and its electrical resistivity can increase from a few $\Omega \cdot m$ up to a few 10's of $\Omega \cdot m$ in a very short distance (<500m), especially in the eastern side of the survey area where resistive silicified sediments can be found amongst conductive seawater filled sediments. Such a short contrast of resistivity will give rise to a static-shift effect on the CSEM measurements (MacLennan and Li, 2013), similar to what can be observed on MT data.

To correct for this effect, we have used the results from the airborne EM survey as inductive methods do not suffer from such effects (Sternberg, 1988). The CSEM static shift correction is calculated by fitting the high frequency amplitude response to the modelled response computed on the resistivity model obtained from the inversion of the airborne EM data, typically for frequencies greater than 100Hz. For CSEM stations located on the eastern side of the survey area and where shallow layers are rather heterogeneous (figure 2), significant static shift corrections are required. However, on the western part of the survey, shallow sediments are rather conductive and homogeneous and CSEM data do not require significant static-shift corrections.

c) 1D CSEM/AEM modelling/inversion results

Once data have been processed and static-shift corrected, we inverted them by determining the resistivity of a multi-layered earth model for each CSEM station. During this process, we fixed the resistivity of the shallow layers with the resistivity obtained from the inversion of the airborne EM data. When not available, we used the high frequency CSEM dataset to estimate it. Fortunately, such points are located in the western area of the survey where shallow layers are rather homogeneous and conductive and hence unlikely to be biased by large static-shifts corrections.

Because of a lack of a fast and accurate algorithm to compute the electric field at various frequencies accounting for the complex transmitter geometry and current injection parameters (e.g. cable geometry, metallic boreholes casings), we have approximated the transmitter as a finite length dipole at the ground surface. 1D modelling of the current flowing in the metallic casings shows that this approximation is valid as the shallow layers are very conductive and most of the current exits the borehole in the shallow section. Figure 3 shows the resistivity maps recovered at 25m, 100m, 250m and 1000m depth over the area of interest.



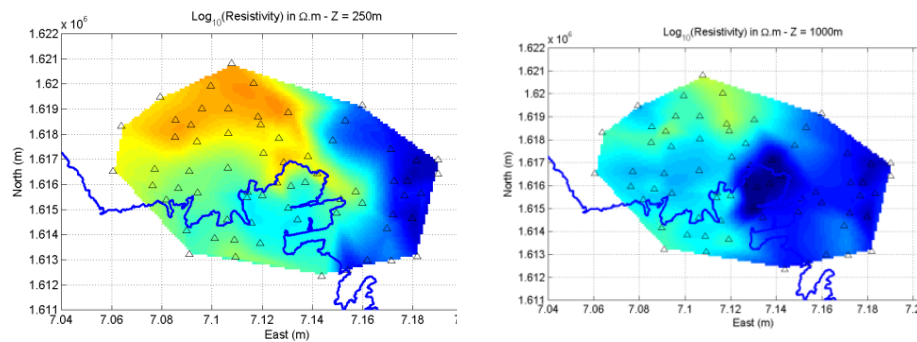


Figure 3: Resistivity maps recovered at 25m, 100m, 250m and 1000m depth from the 1D inversion of the CSEM dataset with static shift corrections from the AEM data. Black triangles represent the CSEM recording stations.

2.4 AEM/CSEM data interpretation

As evidence in the geothermal exploration wells, the very shallow conductive layers ($< 5 \Omega.m$, depth $< 100m$) match well with the presence of unconsolidated sediments as well as highly altered volcano-detritic sediments. In the western part of the survey area, a deep conductive layer ($5-10 \Omega.m$, depth $100m-500m$) is present and corresponds well to the presence of altered volcanic-detritic sediments. This could be the caprock of a geothermal system made of medium temperature alteration minerals ($< 100 \text{ degC}$) like smectite (Ussher et al, 2000). At greater depths, the resistivity increases in the $10-100 \Omega.m$ range and would correspond well to the former high temperature geothermal reservoir itself with high temperature alteration minerals like illite/chlorite. In the eastern part of the survey area, resistivities are high at all depths ($> 100 \Omega.m$) and correspond well with the presence of the volcanic substratum composed of highly resistive low permeability sub-marine breccia.

3. ANSES D'ARLET AREA

3.1 EM survey objective

The study area is located in the southwestern tip of the Martinique Island (figure 4). This area has been volcanically active for the last 1.5 million years as evidenced by the numerous volcanic domes (e.g. Mornes Larchet, Morne Jacqueline, Roches Genty). This magmatic activity was combined with an intense hydrothermal activity as evidenced by the large alteration zones outcropping in the area. Nowadays, only one thermal spring is left in the area, releasing fluid from an estimated 200°C reservoir (Gutierrez et al., 2014). An integrated geological, geochemical, geophysical and hydrogeological study (Gadalia et al., 2015) concluded on a high likelihood of the presence of an active geothermal system in this area but the density of geophysical measurements (especially MT, less than one station per square km, figure 4) was deemed insufficient to ensure a high probability of success of exploration wells. In an attempt to accurately map the drilling targets, a high-density EM survey (more than 10 points per square km) was carried out in Spring 2019.

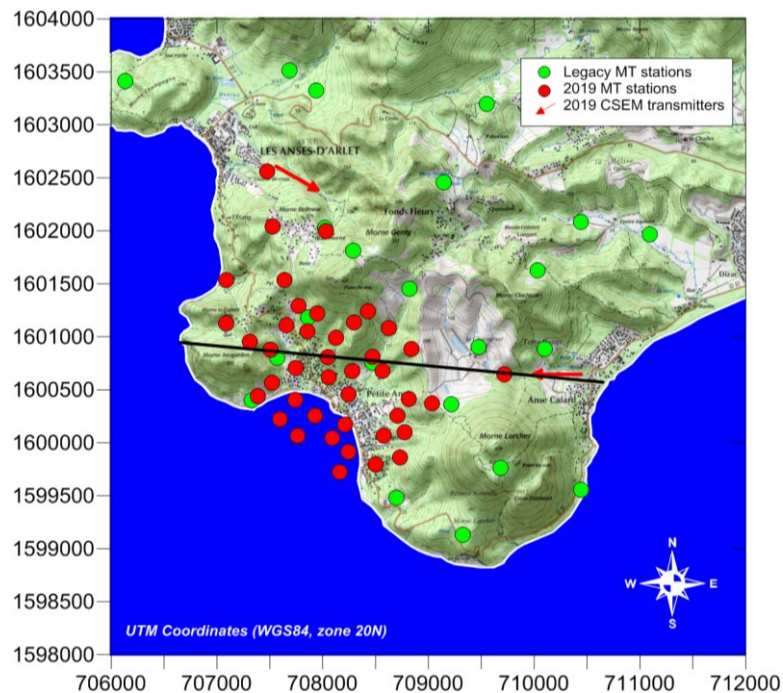


Figure 4: Anses d'Arlet area with locations of the MT stations acquired before 2019 (green dots) and MT/CSEM stations acquired in 2019 (red dots). The black line represents the inverted CSEM profile.

3.2 CSEM and MT survey

The CSEM survey was acquired using two transmitters injecting current in surface electrodes, as no metallic casings was found in the area of interest. The airborne EM survey results were used to identify high conductivity areas where injection electrodes were installed. This strategy ensure a good electrical coupling between the electrodes and the earth and we managed to inject repeatedly current of about 30A. To adequately characterize the subsurface, a broad band of CSEM frequencies (fundamental frequencies from 0.125 Hz up to 512 Hz increasing with a factor 4) was acquired with a minimum of 150 cycles at low-frequencies to ensure proper stacking of any random noise. The waveform was a square wave to ensure powerful harmonics to be measured as well. A total number of 42 CSEM/MT recording stations were deployed on the Anses d'Arlet area (figure 4), 34 onshore and 8 offshore. They were Metronix ADU07 or ADU08 acquisition systems, MFS07 or MFS06 magnetic coils and 2 orthogonal electric dipoles from 20 to 100m long.

Raw CSEM data have been processed in the frequency domain using a proprietary code. After automatic and manual quality control of the processed data, 25% of the data was rejected due to high levels of noise. The remaining 75% of the data were considered of good quality and subsequently inverted. In total, 35 frequencies (= fundamental frequencies + frequencies up to the 9th harmonics x 7 transmitter frequencies) have been processed to provide a broadband signal and allow an easy removal of noisy frequencies bands (e.g. industrial noise at 50Hz and harmonics). At this stage, we only worked with the amplitude of the maximum axis of the polarization ellipses of the horizontal electric field as their spectra are a lot smoother and hence easier to quality control than individual horizontal components (which can sometimes cross zero and hence be confused with noise).

Seven stations were used for MT acquisition during the night shift. Each MT station dataset consists in one hour of recordings at 4096Hz sampling frequency and at least 12 hours at 512 Hz. A distant synchronous MT station, located 50 km away, was used as a remote reference. MT processing is still ongoing and will be reported at a later stage.

3.3 CSEM inversion

For the CSEM inversion, we used the 2.5D MARE2DEM inversion code (Key, 2016). We inverted the amplitudes of the PE major axis of the horizontal electric field from seven CSEM stations located on an Est-West profile close to the thermal spring and for the Eastern transmitter (figure 4). Inverted frequencies were 1/32s, 1/8s, 1/2s, 2Hz, 8Hz, 32Hz since they correspond to the peak fundamental harmonics of the transmitter waveform while still covering a wide range of frequencies. We limited the frequency band on the high side to 32 Hz due to the presence of strong external noise (e.g. 50Hz and harmonics, industrial noise). Target RMS misfit was set to one and final misfit is 13, good enough to provide a preliminary inversion result.

The starting model of the CSEM inversion was a homogeneous 2 Ohm.m half-space with around 6000 total free parameters in the zone of interest. Topographic variations were included in the inversion process. Three levels of grid refinements were used to image properly shallow and deep structures beneath each receiver station (mesh from 50, 100, to 250 meters size). At this stage no static-shift corrections were applied to our input data. The static shift correction base on Airborne EM data is currently being implemented using the same procedure as described in the Lamentin inversion.

The resulting resistivity model is shown on figure 5. Although this is a first-pass inversion, the main geological structures of interest are present on this cross-section, namely:

- A shallow conductive ($<5 \Omega.m$) 500m-thick layer, most likely corresponding to the alteration zone ("cap-rock"). This layer is covered by resistivity bodies at each topographic highs, corresponding to the recent unaltered lavas
- A deep more resistive (5-20 $\Omega.m$) layer in the Eastern part of the survey area, most likely corresponding to the targeted geothermal reservoir
- A deep highly resistive ($>50 \Omega.m$) layer in the Western part of the survey area, most likely corresponding to a volcanic dyke

We also observe a clear boundary between the highly resistive feature and the alleged geothermal reservoir around receiver 30/37. This is of paramount importance to define the drilling targets of the exploration boreholes, as highly resistive rock are unlikely to contain any exploitable geothermal fluid. To confirm these observations, 3D CSEM inversions will be performed on the dataset, including airborne EM and MT data.

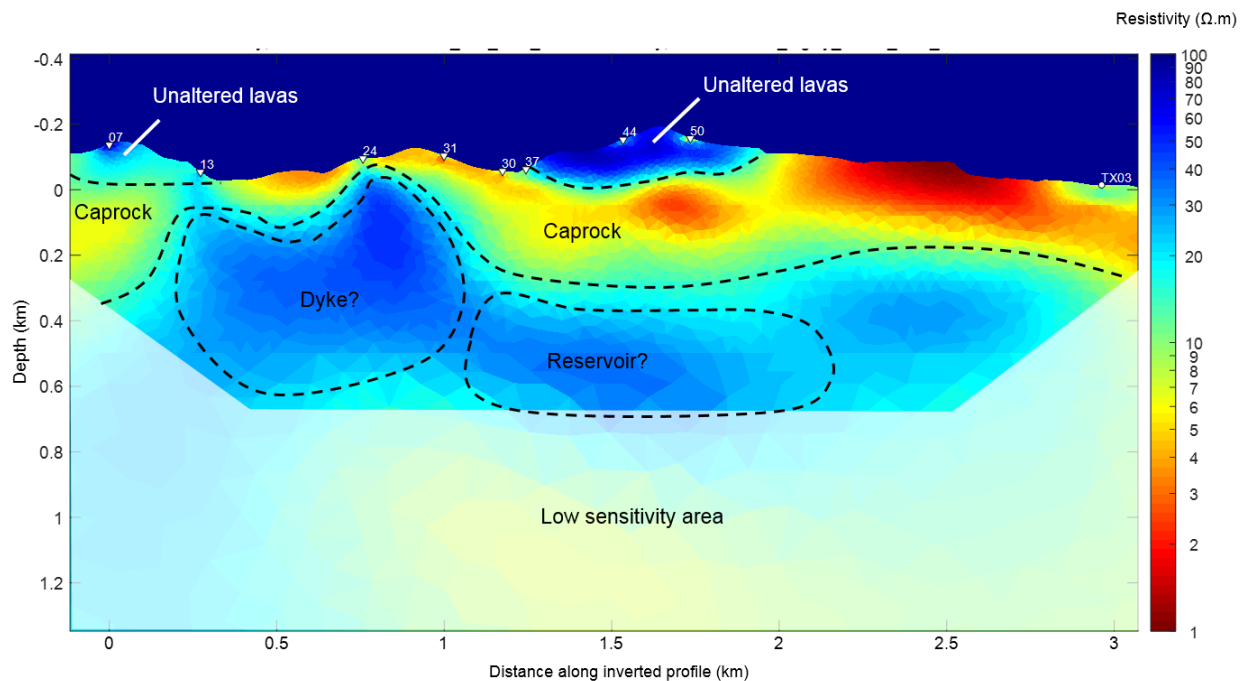


Figure 5: Resistivity model derived from the 2.5D inversion of seven CSEM stations located on an Est-West profile close to the thermal spring and for the transmitter TX2.

CONCLUSION

Exploring for underground resources using land-based electromagnetic methods can be very challenging in volcanic islands. We have shown that a combined airborne and land-based controlled-source EM approach can provide an attractive alternative to image resistivity variations at depth in such a context. In particular, it does efficiently tackle the issue of static-shift correction of CSEM data in the presence of near surface heterogeneities. We believe this work sets the foundations for a more robust geophysical exploration workflow in challenging EM environments.

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