AEM2023
8th International Airborne Electromagnetics Workshop
3-7 September 2023
Fitzroy Island, QLD, Australia
Contact: aemconference@theassociationspecialists.com.au
HOSTED BY
Australian Society of Exploration Geophysicists

AEM imagery down to one kilometer depth: New constraints for geological and hydrogeological modeling in volcanic contexts

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SUMMARY

We present the integration of airborne magnetic data and five different airborne electromagnetics data sets spaning from 3 000 NIA up to 1 000 000 NIA magnetic moments (three different AEM systems were used) in La Réunion volcanic island. Subsequently, a 3D geological model of the first kilometer beneath the Plaine des Fougères was built, in order to constrain 3D hydrogeological modeling.

This approach allowed for the correlation of different datasets, providing a comprehensive image of the subsurface and enabling a greater hydrogeological understanding. It was used to position the route of a deep water drainage gallery and has great potential for applications in other areas.

Key words: Airborne electromagnetics, Time Domain ElectroMagnetics, aeromagnetic, volcanic island, geological modelling, hydrogeological modelling

INTRODUCTION

In order to bring fresh water to the northern part of La Réunion volcanic island (Indian Ocean), the County Council of La Réunion (CD974) requested an assessment of the geological and hydrogeological risks related to the drilling of a new water drainage gallery at great depths (300 to 1000 m) below the Plaine des Fougères. This new "GANOR" gallery will be connected to the existing deep GSAM gallery, which is covered by up to 1000 meters of volcanic materials. To assess the risks, BRGM has established a 3D geological model. This model then supported a 3D hydrogeological model in order to identify potential hydrogeological risks of drilling in the surrounding of highly permeable aquifers under high pressure. Peyrefitte et al (2022) present this work in a technical report.

The local geological map exhibits very monotonous surface information, mainly with lava flows and tuffs PN3 and PN4 (Figure 1). The few existing soundings in the area never go deeper than a few dozen of meters.

DATA ACQUISITION

In 2014, an airborne electromagnetics (AEM) survey was conducted using the SkyTEM 304 system over the entire La Réunion island. This survey gave an image of the first 300 meters (line path in Figure 1).

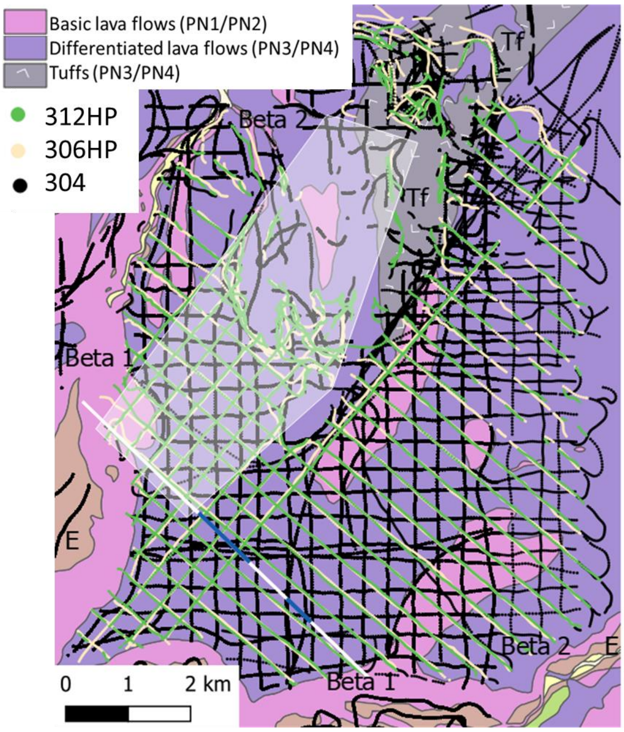

Figure 1: Geological map over the Plaine des Fougères. GSAM gallery is represented with a white line, the possible area of the future gallery in a white polygon and in blue, the aquifers crossed during the GSAM drilling. Airborne acquisitions are represented in black (304 system), light orange (306 HP system) and green (312 HP system).

A first study creating a 3D geological model combining this AEM dataset with magnetic modelling was performed. To allow a preliminary geological/ hydrogeological interpretation, the lack of resistivity information at great depths, but also the lack of rock magnetization data, resulted in a preliminary understanding of the deep hydrogeology. This result was promising, but still highly hill-constrained.

Two surveys were then flown in 2021 over the Plaine des Fougères area, using SkyTEM 306HP and SkyTEM 312HP systems in order to extend the imagery, down to 1 000 m depth. These two new AEM datasets and the previous one are presented in Table 1. Figure 4 is an example of South-North resistivity profiles, illustrating the increase of investigation depth: SkyTEM 304 images resistivity up to 200-400 m depth, whereas SkyTEM 306 HP and 312 HP system reach 800-1000 m depth in this area, down to a maximum of 1200 m. Combining the three AEM datasets, a high-resolution / deep penetration 3D resistivity block of the Plaine des Fougères was generated from the surface down to 1000 m depth.

The careful preprocessing of each dataset, their inversion and their combination into a single resistivity model is explained below.

DATA PROCESSING

BRGM processing methodology of AEM data is presented in Reninger et al (2020), it includes the use of the singular value decomposition (Reninger et al., 2011). Also, to increase the signal/noise ratio, this processing includes an adaptative stack that changes its span according to the noise level, optimising resolution and depth of investigation. A manual editing of the residual noise was also achieved to complete the processing of each EM dataset. Such a processing strategy has proven to be essential for imaging resistivity contrasts up to one kilometer.

A joint smooth SCI inversion (Viezzoli et al, 2007) was run considering all AEM datasets. This inversion resulted at the location of each AEM data in a 1D-resistivity model, made of 40 layers, having a fixed thickness and variable resistivity with depth.

A 3D resistivity model was then generated by the interpolation of the 304 and 306HP 1D resistivity models for the near surface (the first 200 m) and the interpolation of 306HP and 312HP 1D resistivity models for greater depths (from 200 to 1000 meters); the estimated depth of investigation was taken into account for interpolating data. The resulting 3D resistivity model takes full advantage of the resolution of the 304 and 306 HP systems for the 200 upper meters and of the depth of investigation of the 306HP and 312HP systems for mapping deeper geological bodies, allowing for greater modelling of the geological structure and understanding of the hydrogeology of the Plaine des Fougères.

During the AEM surveys, airborne magnetic data were also acquired. They were all combined to obtain a high-resolution magnetic map. Given that the surveys were conducted with the same magnetic instrumentation and parameters (acquisition height, diurnal removal, the assembly was quite simple: data points measured along flight lines of the surveys were checked for consistency and subsequently gathered in a common database. A high resolution 100 m magnetic anomaly grid was derived using a simple interpolation of this new combined dataset (Figure 2).

Oriented rock sampling was made by geologists over the area from May to June 2021. A sample magnetisation library was compiled, combining laboratory measurements (performed on oriented samples with a JR5-A magnetometer) and field magnetic susceptibility (with a kappameter). This library provides rock magnetization constraints for deposits of each activity period of the Piton des Neiges (the volcano on which is located the study area). A total of 75 rock samples were used as reference for further magnetic modelling.

Taking into account the volcanic history, 2D magnetic modeling was conducted, using the geological map, the AEM resistivity model as background preliminary geometry and rock sample magnetic measurements to constrain the geological magnetic responses. The obtained modelling generated geologically realistic cross-sections (example in Figure 5).

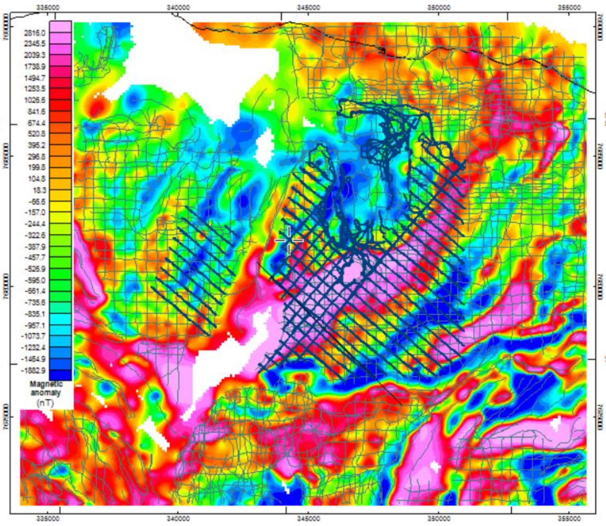

Figure 2: Magnetic anomaly map made with the fusion of 2014 and 2021 surveys (green lines show 2021 flight path).

The resistivity model provided the overall geometry of the volcanic layers and their degree of alteration. The magnetic data refined the geological model in depth, thereby highlighting distinct geological units within relatively homogenous resistivity layers.

The integration of the different datasets had the added benefit of providing a more detailed geological understanding of the area and allowing for more accurate interpretations of the hydrogeology.

RESULTS

Combining all the available geological information with series of 2D geophysically constrained cross-sections, a 3D geological model was derived all over the Plaine des Fougères on a depth range of -1000 m below the topography (1500 meters above sea level). We used GeoModeller® software which previously proved to allow the successful integration of geophysics in complex 3-D geological models (e.g. Martelet et al. 2004; Calcagno et al. 2008). Figure 3 displays the resulting 3D geological model, built up upon geological units classified by their increasing age, ranging from PN0 to PN4. Based on the interpretation of resistivity signatures, some of the modelled units are differentiated based on their alteration or water saturation.

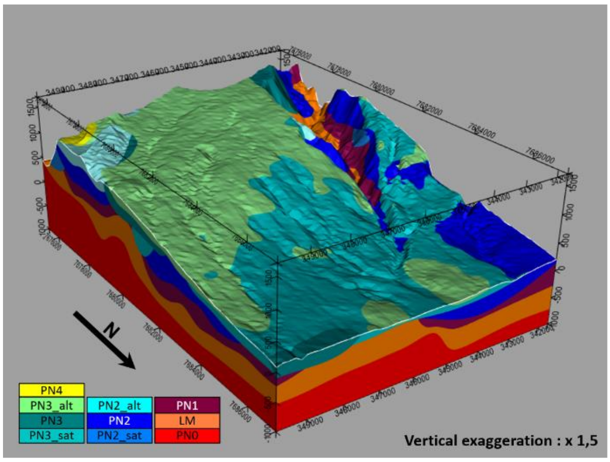

Figure 3: 3D geological model of Plaine des Fougères.

The 3D geological model was developed to assess the hydrogeological risk of different scenarios of gallery route. The 3D model was therefore implemented in a hydrogeological model performed in Visual KARSYS, a free software designed for assessing hydrogeological risk (Malard et al, 2018). The 3D geological geometries were used as input (as well as springs, geological sounding…) to simulate the hydrogeological conditions within the 3D model. The analysis of this hydrogeological model was focused along several possible gallery routes. Taking into account the expected lithological and hydrological characteristics of the modelled geological layers the hydrogeological risk was assessed, along the different gallery routes, depending on the proximity of overlying aquifers and hydraulic head.

CONCLUSIONS

Combining high-resolution near surface and deep AEM surveys with aeromagnetic data, geological knowledge and rock sample measurements, it was possible to generate a comprehensive 3D geological model down to a depth of 1000 meters below the Plaine des Fougères. The deep AEM investigation was possible with the combination of a high power emission and a resistive underground (mainly above 300 Ohm.m in the first 400 meters). The generated 3D geological model allowed for the characterisation of the subsurface materials, as well as a better understanding of the geological structure and hydrogeological system of the area. This made it possible to map geometry of hydrogeological bodies within the first kilometer below the surface, and thus reduce the risk associated with the drilling of a deep gallery. Since, previous deep tunnelling in the area faced enormous difficulties (and loss of money), anticipating the geological and hydrogeological environment of tunnelling is of utmost importance to mitigate the geological risks prior committing heavy construction operations.

ACKNOWLEDGMENTS

This project is funded by the County Council of Réunion (CD974) and the Water Office of La Réunion. We thank the University of La Réunion for cooperation in sampling volcanic rocks.

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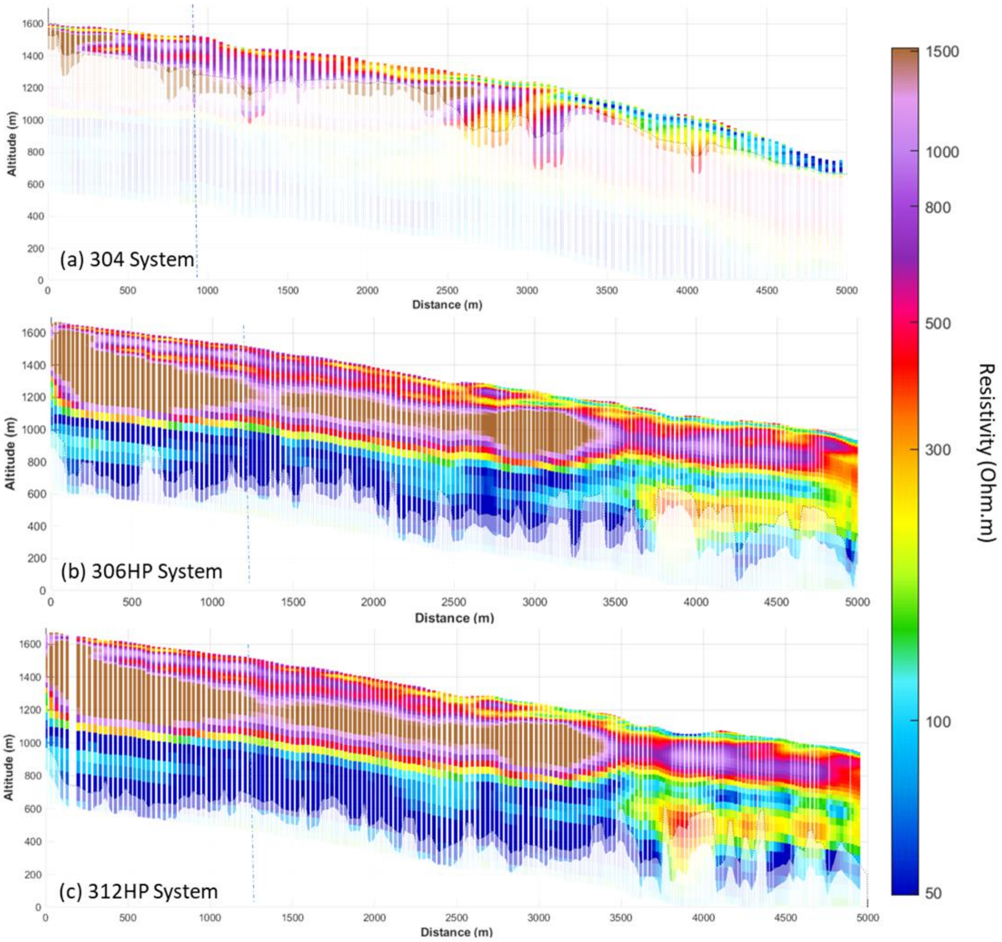

Figure 4: South-North resistivity profiles acquired with 304 (a), 306HP (b) or 312HP (c) systems in the Plaine des Fougères area. (a) is oriented S/N, (b) and (c) are overlapping, SW/NE. Dotted blue line shows a point where lines are intersecting.

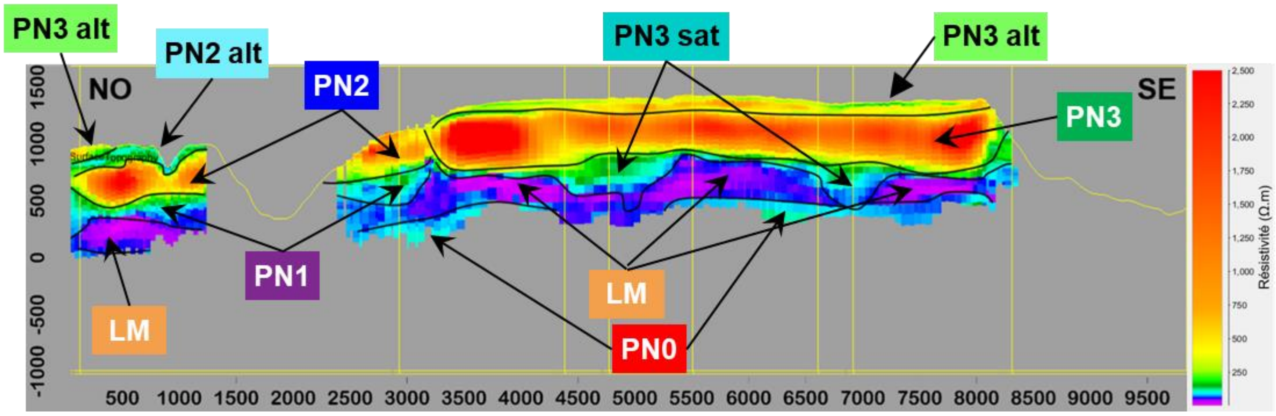

Figure 5: Example of an interpolated resistivity profile along the existing underground Salazie amont gallery, with geological interpretation. PN0 to PN4 represent old to recent volcanic formations.

Parameters	**304 (2014)**		**306 HP (2021)**		**312 HP (2021)**
	LM	HM	LM	HM	HM
Used time gates	6.8 µs to 5.53 e -4 s	60.42 µs to 8.9 ms	6.6 µs to 4.8e-4 s	351 µs to 1.02e-2 s	1.06 to 13.79 ms
On Time	800 µs	10 ms	1 ms	5 ms	5 ms
Off Time	738 µs	10 ms	0.5 ms	15 ms	15 ms
Number of gates used	20	28	41	26	27
Number of turns	1	4	1	6	12
Loop surface	340.82 m²	340.82 m²	342 m²	342 m²	342 m²
Repetition frequency	325 Hz	25 Hz	333.33 Hz	25 Hz	25 Hz
Flight line spacing	400 m	400 m	400 m	400 m	400 m
Kilometers of data	489 km used in this project	489 km used in this project	232 km	232 km	226.5 km
Average height	82.8 m	82.8 m	51.1 m	51.1 m	54.2 m
Average current	9.2 A	117 A	8.72 A	240.9 A	229.7 A
Cut-off duration	3.34 µs	50 µs	6 µs	272 µs	985 µs
~ Magnetic moment	3 000 NIA	160 000 NIA	3 000 NIA	500 000 NIA	950 000 NIA

Table 1: Comparison of acquisition parameters during the 3 AEM surveys used in this study.