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Electromagnetic Mapping of Subsurface Formations in the Lower Northeast Rift Zone of Piton de la Fournaise Volcano: Geological and Hydrogeological Implications

M. Courteaud and B. Robineau
Laboratoire des Sciences de la Terre, Université de la Réunion

M. Ritz and M. Descloitres
ORSTOM, BP 1386, Dakar, Sénégal

ABSTRACT

Time-domain electromagnetic (TDEM) and audiomagnetotelluric (AMT) surveys were conducted on the lower northeast rift zone of Piton de la Fournaise volcano, as a part of a groundwater exploration project. The objective of the study was twofold: (1) to evaluate the possibility of mapping of volcanic medium in areas where little is known about the subsurface geology and to infer shallow geological structure from the electrical interpretation, and (2) to identify formations that may present good aquifers, and subsequently to estimate the relationship between groundwater resources and geological structures. Data collected at 35 locations were interpreted with one-dimensional layered models, which were then pieced together along survey lines to make electrical cross sections. From the surface down, the cross sections have revealed that the rift zone consists of subhorizontal layers having resistivities ranging from greater than several hundred ohm meters to less than 8 ohm-m at moderate depths. The study suggests that the investigated area can be broadly divided into two hydrogeological sections. The southern section, bounded by the Bois Blanc cliff, is consistent with a simple coastal groundwater system, where the freshwater lens rests on the saltwater. In the northern section, the saltwater wedge appears to be disturbed by the presence of a clayey, poorly permeable basement at depths close to sea level. The aquifer boundaries appear to be well defined and delineated. The hydrogeological features of the study area are found to be mainly dependent on the tectonic evolution of the rift zone.

Introduction

Piton de la Fournaise volcano, one of the most active volcanos in the world, covers the southeastern part of Reunion island (SW Indian Ocean). In the last years, development of coastal areas have increased the groundwater demand for agricultural and urban purposes. In these areas, like for most young volcanic islands, the general hydrogeological assumption -the so called "basal aquifer"- appears as a freshwater body lying on seawater toward a saltwater wedge. This basal groundwater system is merely recognized and characterized by low piezometric levels and gradients (Join and Coudray, 1993), explained by the very permeable lavas of the young and effusive Piton de la Fournaise volcano. The saltwater location is the main limitating factor for the water resource, and mixing with the overlying freshwater body may seriously affect the water quality of nearby local wells and drillholes. For these reasons, it is expedient to study seawater intrusions in coastal aquifers using geophysics in order to evaluate the need for further action. Because of the large differences in resistivity between unsaturated and saltwater saturated formations, electromagnetic methods have become well established for the investigation of coastal aquifers. The electrical properties of subsurface formations are highly dependent upon porosity, saturation, and pore fluid resistivity (Keller and Frischknecht, 1966) and information about water content and water quality can be obtained. Electromagnetic (EM) methods are used to map the freshwater-saltwater interface and more generally, for studying conductive bodies of hydrogeological interest (e.g. Stewart, 1982; Goldman et al., 1991).

In this paper we present the results of an EM survey aimed at the geological/hydrogeological study of Sainte-Rose coastal area (fig. 1). Very little is known about the geometry and the hydrological characteristics of aquifers, specially inland, because drillhole information is lacking or sparse. To provide information on the distribution of aquifers we have used the combination of two EM techniques: time domain electromagnetic (TDEM, e.g. Fittermann and Stewart, 1986) and audiomagnetotelluric (AMT) soundings (e.g. Strangway et al., 1973). The TDEM survey was done to study shallow structures and the AMT survey to investigate deeper structures, and in particular to test the presence of deep conductive bodies.

The EM survey consisted of 35 TDEM and AMT soundings (fig. 1) on a total area of the order of 10 km^2. The availability of suitable sites was considerably restricted by logistical difficulties. The presence of thick scrub, few tracks and

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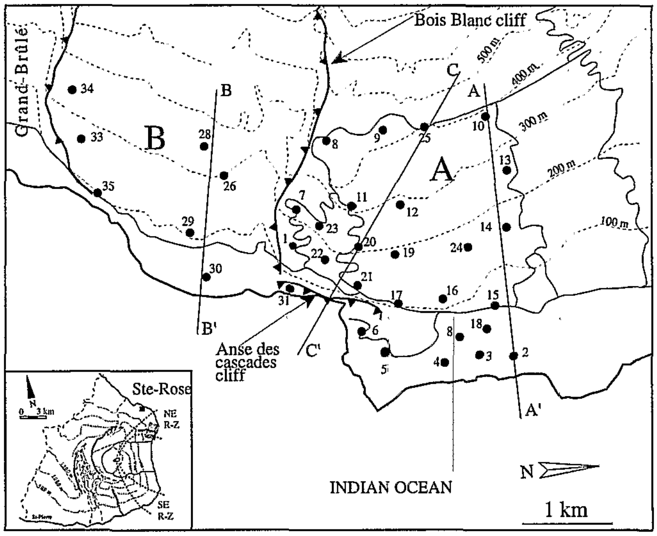

Figure 1. Location of EM sites (black circles) in relation to major morphological features of the lower northeast rift zone of Piton de La Fournaise volcano. Also shown is the location of three profile lines A-A', B-B' and CC'. Bois Blanc cliff delimits zones, A and B, with different electrical characteristics. The elevation contours are in meters. The inset map shows the location of the investigated area on Piton de La Fournaise volcano.

rugged topography prevents more widespread coverage.

From a geological point of view, Piton de la Fournaise shield volcano presents a dominant effusive activity concentrated in the summital areas, but part of the eruptions occurs along two arcuate rift zones -namely the N-E rift zone and the S-E rift zone- that run from the summit to the coast (fig. 1). Located on the N-E rift zone, the coastal area of Sainte-Rose displays many large scoriaceous vents, marking out past eruptive events. A major E-W structural feature, Bois Blanc cliff, cuts across the study area. Its significance is still speculative, but some authors (Bachelery, 1995) interpret the cliff as the northern boundary of an ancient flank slide. The volcano-structural context is then complex but no drilling has given information on the deep geology. Only surface volcanic formations have been surveyed and the geological map shows mainly recent volcanic flows with some interbeded pyroclastic layers. In addition to our groundwater objectives, delineation of geological structures and their relation to groundwater resources is another important opportunity of this work.

EM Survey

The TDEM method uses the interaction of a transient EM wave with the earth to determine the electrical resistivity of the earth as a function of depth. The method has been described in detail and for a complete description the reader is referred to Nabighian (1991). A central-loop configuration was chosen for our work because of its enhanced signal-to-noise ratios and reduced sensitivity to lateral resistivity gradients (Eaton and Hohmann, 1989). The instrument used was the Geonics TEM47 with two or three base frequencies. Response curves are inverted with the software TEMIXGL (Interpex Limited, 1989) to produce a one-dimensional (1-D) electrical model for the earth beneath each loop.

The AMT equipment used in our investigation consisted of Tensor Iris Instruments SAMTEC2 system. The AMT method is based upon the measurements of natural EM field fluctuations at the earth's surface in the frequency range of 1 to 10^4 Hz (Strangway et al., 1973). AMT measurements are represented as a complex impedance tensor relating the electric and magnetic field values and are usually expressed as apparent resistivity and impedance phase in the orientations (TM and TE modes, perpendicular and parallel to the strike) of the principal axes of the impedance tensor (Vozoff, 1972). When the earth is to be investigated with the AMT method, near-surface inhomogeneous structures such as rough topography and shallow resistivity anomalies may cause local distortions (static shift effects) of electric field much more than the magnetic field (Berdichevsky and Dmitriev, 1976). Interpretations based on those data will be then erroneous. Using the TDEM method that measures only the magnetic field for

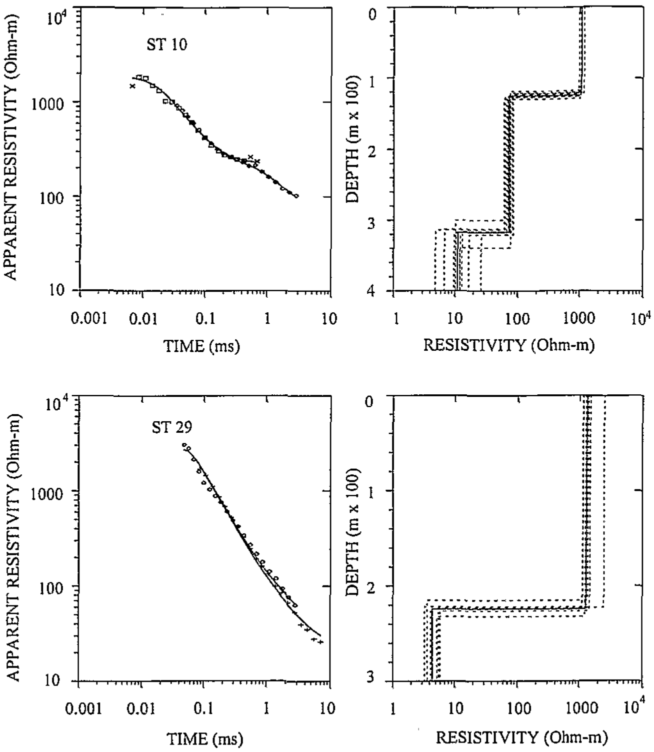

Figure 2. TDEM data collected at two typical sites and calculated responses for the best-fit models (solid lines) shown in the right-hand graph with the equivalent models (dashed lines). Symbols in the left-hand graph represent three-frequency field data.

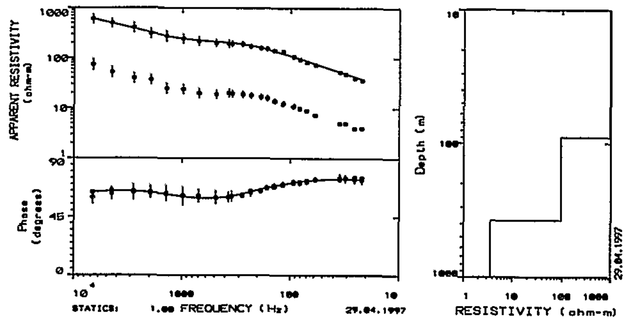

Figure 3. Examples of AMT data at site 25 showing the effect of near-surface inhomogeneities as evidenced by the very pronounced parallel solit between the TE (lower curve) and TM amplitude curves. Solid line is the best-fit inverted layered model (shown in the right-hand graph) corresponding to the TM data.

subsurface characterization, it is possible to obtain data valuable AMT in reducing the static effect (Pellerin and Hohmann, 1990). This correction method can be applied only to a horizontally layered resistivity structure. One limitation of the TDEM-based procedure is that an overlap between the TDEM and AMT sounding curves at the same location is necessary for the technique to be effective. In the study area, the recorded time windows provide adequate overlap (approximately one decade) with the AMT data window. Consequently, the AMT data affected by static shift in a 1-D environment are correctable using the TDEM-based analysis.

TDEM soundings

All the sites in the study area are characterized by the same type of the sounding curve which gives a monotonic decrease in apparent resistivity with time. Such curve behaviour undoubtedly proves the presence of a low-resistivity layer at the bottom of the section. Figure 2 shows two typical TDEM soundings performed over the northern (site 10) and southern (site 29) sides of the studied area (fig. 1). The first step in interpretation of TDEM measurements was to invert the apparent resistivity curves into 1-D resistivity stratification. The data were interpreted with the minimum number of layers that gave a good fit. Starting two- or three-layer models, where resistivity decreases with depth, were used to simulate apparent resistivity data measured in the field. Figure 2 shows the 1-D electrical models obtained from inversion of the data at two typical sites in the form of the equivalent resistivity vs. depth sections.

AMT soundings

Tensor AMT measurements were carried out with the telluric sensors oriented along N-S and E-W at each location. Tensor analysis (Vozoff, 1972) of the AMT data indicates that the AMT soundings are isotropic for almost all considered frequencies. Some exceptions to the isotropic character are observed at sites 14 and 25 which have been affected by different amounts of static shift, consisting of parallel splitting of the two observed mode curves. Figure 3 shows an example of this bilateral splitting from site 25. In this case, the shifted AMT apparent resistivity curves are corrected by using the TDEM-based procedure. Other exceptions to the isotropic character are observed at some sites near the coastline where the two orthogonal AMT polarization data exhibit marked lack of parallelism of the curves, indicating an anisotropy situation in the vicinity. The AMT responses at these coastal sites are affected by the coastline and seawater (coastal effect, e.g. Ogawa, 1987). To see the coastal effect, we calculate and compare the responses for two simple 2-D theoretical models (Wannamaker et al., 1987), with and without ocean. The results (Descloitres et al., 1997) indicated that the TE mode data are biased by the presence of the ocean. In contrast, the TM mode data are relatively little affected by the ocean across the observational bandwidth. Consequently, the TM mode data at sites close to the coastline have been emphasized in the 1-D modelling process. The determinant AMT sounding data (Ranganayaki, 1984) from the sites free of static shift and not influenced by the ocean are chosen to provide an accurate assessment of the vertical resistivity structure.

Figure 4 shows typical determinant apparent resistivity and phase data divided into two groups, A and B. Group A (typical site 10) presents a flattening more or less pronounced in the intermediate part of the curve with a rapid descending final branch. Group B (typical site 26) is characterized, in general, by a continuous decrease in resistivity with frequency,

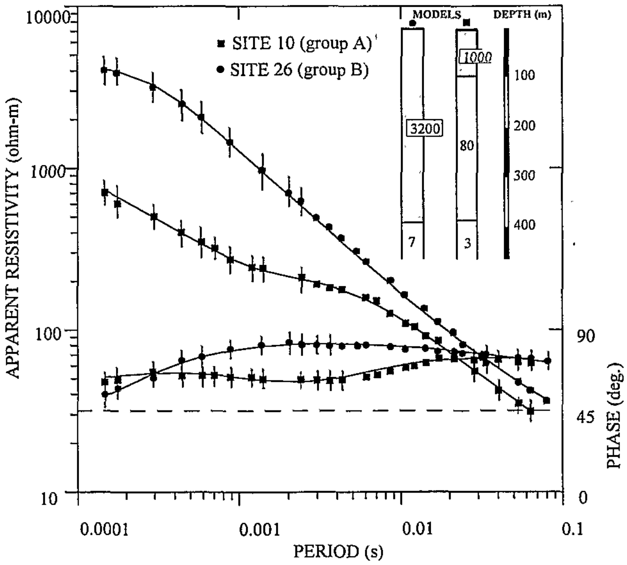

Figure 4. Examples of determinant apparent resistivity and phase sounding data at sites 10 and 26 with error bars (95 % confidence intervals, not plotted when smaller than the symbols) and computed 1-D model response curves.

without any other prominent feature. All the sounding curves reveal a decrease in apparent resistivity with decreasing frequency, at the end of the measurement range. This typically indicates a conductive layer of infinite-thickness.

Individual 1-D inversions (Jupp and Vozoff, 1975) of AMT responses recorded in the survey area were conducted at each site, taking into account the presence of significant distortions in the data at some sites as discussed above. Modelling of the near-surface resistivity and depth has been guided by using layered models that matched the TDEM models as much as possible. The calculated curves for the best fitting layered model at selected sites are shown in fig. 4. Model sensitivity was investigated (Jupp and Vozoff, 1975) to determine whether the final models are well constrained, or whether large parameter variations are allowed. Generally, all physical parameters of resistivity and thickness are reasonably well resolved except for some of them in the uppermost layers. The accuracy of the 1-D models is difficult to evaluate. However, confidence in the models is inspired by the very small deviations between the TDEM and AMT apparent resistivity data in the overlap high-frequency region of the AMT curves. There is no major disagreement between two completely different EM methods.

Electrical cross sections

The results from the 1-D inversion of the TDEM and AMT soundings were compiled and plotted along two profile lines located in fig. 1. Two interpreted resistivity vs. depth cross sections are shown in figs. 5 and 6.

Cross section A-A' (fig. 5) represents the behaviour of the northern side of the studied area, bounded to the south by the Bois Blanc cliff (fig. 1). The cross section shows a consistency from sounding to sounding and a pattern of smoothly varying structure. The main features of the derived structure, from the surface downward, may be summarized as follows: (1) a surface layer of 500-900 ohm-m resistivity that is 20-100 m thick. Its thickness increases, in general, with increasing distance from the coast, (2) a layer of 50-100 ohm-m resistivity and a thickness of about 50-270 m. Its thickness increases with surface elevation, and (3) a conductive basement with resistivities of less than 8 ohm-m. The depth to this conductor varies along the profile from 40 m below mean sea level (MSL) at coastal sites to more than 25 m above MSL at inland sites.

A similar structure with three layers is recognized along line B-B' (fig. 1) but with higher resistivity values and some interesting differences. Cross section B-B' (fig. 6) indicates the following layers: (1) a high-resistivity first layer (1000-5000 ohm-m) 60-250 m thick extending, in general, to a depth close to MSL, (2) an intermediate-resistivity second layer (100-300 ohm-m) which thickens from 30 m close to the coast to as much as 200 m inland, and (3) a basement of low-resistivity of less than 6 ohm-m at an increasing depth with increasing distance from the coast.

Hydrogeologic Interpretation of the Cross Sections

We have attempted to interpret what geological and hydrogeological conditions exist, in a first approximation, in the electrical sequences beneath the northeast rift zone of the volcano.

Southern part

South of the Bois Blanc cliff (fig. 1), the electrical structure along profile B-B' shown in fig. 6, suggests that the surface resistive layer represents dry or unsaturated volcanic flows. The second layer, marked by resistivities of some hundreds of ohm meters and a top approximately coinciding with MSL, could indicate the presence of volcanic flows saturated with freshwater. The low resistivities (< 6 ohm-m) in the third layer can be easily related to the saltwater intrusion zone. As a consequence, the structure of this part presents the typical geometry (Ogawa and Takakura, 1990) of a volcanic coastal aquifer in equilibrium with seawater. Unfortunately, at this stage, no geological and/or hydrogeologic information from drillholes is available to verify quantitative definition of these conditions.

Northern part

As indicated by the cross section A-A' (fig. 5), the basic structure beneath the northern part of the study area comprises three units of high-, moderate-, and low-resistivity from the surface down. Except for the first layer consisting of probable dry volcanic flows, there is a different resistivity distribution from that of the previous cross section. The most interesting feature of the electrical structure from a geological and hydrogeological viewpoint is the presence of a relatively conductive second layer, ranging from 50 to 100 ohm-m, at shallower depths and thickening landwards. The top of this

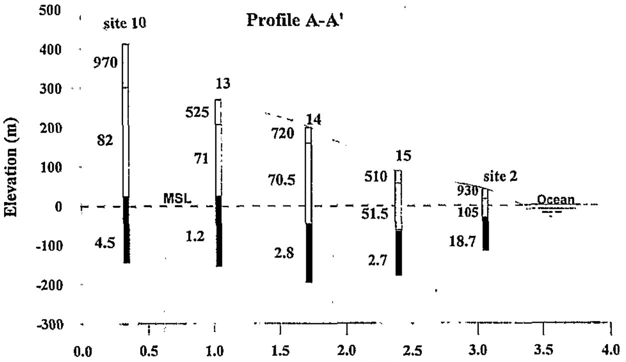

Figure 5. Composite electrical cross sections inferred from transient EM and AMT data along A-A' profile (see fig. 1 for profile location). The near-surface resistivity values were determined from TDEM data. Resistivities are in ohm-m.

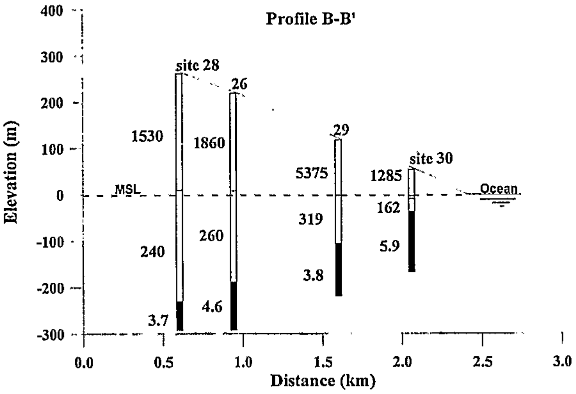

Figure 6. Composite electrical cross sections inferred from transient EM and AMT data along B-B' profile (see fig. 1 for profile location). The near-surface resistivity values were determined from TDEM data. Resistivities are in ohm-m.

layer is above MSL, by several hundred meters at site 10 (fig. 5). The inland portion of the conductive basement remains unexplained by salted formations because its surface elevation tends to increase landward . However, seawater intrusion cannot be ruled out as the cause of the low resistivities modelized beneath MSL at sites located in a narrow coastal area (Sites 15 and 2, fig. 5).

Geological and Hydrogeological Discussion

As seen before, the geoelectrical stratification of the southern sector can be easily interpreted directly in terms of geological and hydrogeological structures : a thick resistive pile of recent lava flows intruded by saltwater supporting a freshwater lens. On the contrary, the lower resistivity of the second geoelectric layer and the morphology of the conductive basement beneath the northern sector need a discussion. Although direct information (drillholes) is lacking, interpretations can be proposed, taking in account recent studies on Piton de la Fournaise structures and our field observations.

Nature of the second layer

It could be noticed that the first layer appears less resisitive in the northern sector, than the one of the southern sector, but such a difference is obviously related to extensive interbeded pyroclastics along the rift zone.

To explain the low resistivity of the second layer, the presence of pyroclastics is not sufficient and other factors have to be proposed. Fortunately the upper part of this layer outcrops along the littoral "Anse des Cascades" cliff (fig. 1) and the geological section (fig. 8) shows two lithologic units. The upper part of the section consists of a pile of recent thin pahoehoe lava flows. The lower unit displays intensely argilized layers of pyroclastics (ash, lapilli, tuf) and volcanic detritals, interbedded with thick olivine-rich lavas; very productive springs underline the geological distinction between the two units and the resulting change in permeability. Because of the continuity of this interface with the top of the second electrical layer along profile CC' (fig. 8), we interpret this layer as a different lithologic layer with a higher clay content, fully or partially water-saturated.

The conductive basement

One of the hydrogeological goals of the present study was to evaluate the lateral extension of the seawater intrusion into the coastal aquifer. Figure 7 shows the top of the conductive basement with respect to MSL. Beneath the southern area, the conductive basement represents the freshwater-saltwater interface. This surface shows a landward dip, and the Ghyben-Herzberg principle (Kashef, 1983) allows us to infer a low piezometric gradient. The contour lines generally follow the coastline and show a sharp south-north deflection changing to a east-western one on the northern side of this part bordered by the Bois Blanc cliff.

The morphology and the nature of the conductive basement beneath the northern sector is quite problematic. Apart from a narrow littoral zone where the resistivity and landward dipping of this basement can easily be interpreted as a marine intrusion, the upper part of this sector shows a very conductive (<10 ohm-m) third layer above MSL and rising up landward (fig. 8). High temperatures, mineralized groundwaters -usually argued factors to explain very low resisitivities in volcanic environments (Fitterman et al., 1988)- are not convincing in our case because no actual thermal nor hydrothermal activity are present in this area. However, weathering and argilization processes along past hydrothermal zones could explain such very low resistivities. Additionally, the

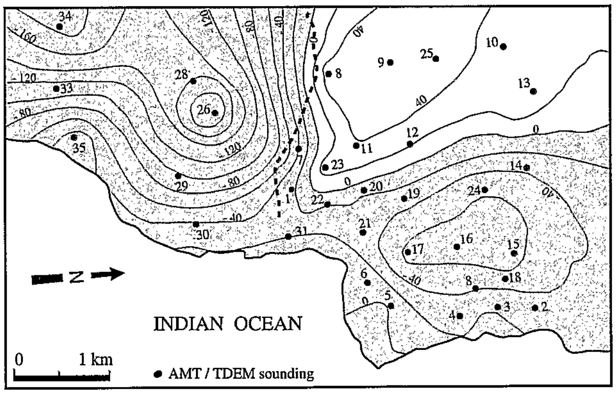

Figure 7. Contour map of the top of the conductive layer (less than 8 ohm-m), in meters with respect to MSL. Contour interval 20 m. In shaded zone, the top of the conductive substratum could be interpreted as the salt-freshwater interface. The dashed line corresponds to the location of Bois Blanc cliff (see fig. 1) and separates two zones with different hydrogeological behaviours as discussed in the text.

presence of clayey landslide materials has been recently proposed to explain the occurence of extensive conductors above MSL beneath La Fournaise flanks (Descloitres et al., 1996), but such an hypothesis is not justified by any volcanic nor morphologic evidences of landslides in this northern part.

A high clay content can objectively be considered as the principal factor to explain low resistivities, but any conclusive interpretation attempted in the way to link the clayey nature of the conductor to a specific volcanological process would be speculative.

It must be noted, however, that recent oceanographic surveys (Labazuy, 1991 ; Lénat and Labazuy, 1990) and magnetic studies (Malengreau, 1995), suggest the presence of ancient volcanic formations (> 0.7 My) beneath the North-East rift zone and offshore. About 4-5 km offshore the northern sector of the study area, an obviously eroded and dissected relief crops out in the prolongation of the rift zone. Taking in account these results, our proposal is to consider that the conductive third layer corresponds to this old basement. Such a proposition implies a paleo-surface located around MSL beneath the northern sector of the study area, with a seaward dipping of about 10 %.

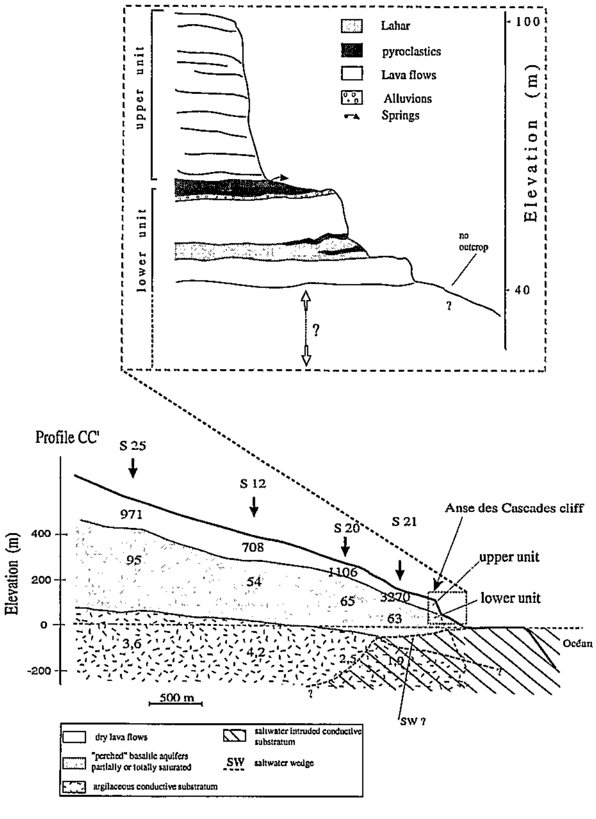

Figure 8. Composite electrical cross section along CC' profile (see fig. 1) in the northern part of the study area. A geological and hydrogeological sketch is proposed. The two first electical layers have been correlated with a geological section (inset figure). Numbers are resistivities in ohm-m.

Hydrogeological consequences

The very conductive basement, seen in the upper area of the northern part, presumably clayey in nature (see before), and found around MSL (sites 10, 13 and 14, fig. 4), could constitute the top of a poorly permeable medium. It could then correspond to a permeability limit that determines the groundwater pattern of the northern part. Located above MSL inland (sites 25 and 12, fig. 8), the basement could support saturated zones and provide high piezometric levels.

Furthermore, such a low permeability basement could stop the seawater intrusion in the coastal area. On fig. 8, profile CC', only site 21 shows a lower conductive electrical basement that can be interpreted as saltwater intruded formations; then the marine intrusion seems to be restricted to a narrow littoral belt in the northern part (fig. 7). For reason of hydraulic continuity, the saltwater wedge might occur further inland, but the dip of the saltwater wedge is supposed to increase sharply when meeting the argilaceous low permeability basement. Unfortunately, the clayey conductive basement cannot be discriminated from the salted one because of similar resistivity values. Nevertheless the hydrogeological context of the northern part appears to be very different than the one of the southern part, where no specific structures disturb the development of the standard basal aquifer in equilibrium with seawater.

This hydrogeological differentiation occurs along a short spatial distance and corresponds to the location of the E-W Bois Blanc cliff (fig. 7).

The hydrogeological influence of this discontinuity highlights - because this cliff has a volcanological significance - the relationship between the volcano-tectonic evolution of a region and its hydrogeological behaviour.

Conclusions

The joint use of TDEM and AMT surveying techniques have proved useful to map the subsurface of structurally complex areas where little geologic information is available due to lack of drillholes. EM surveys can also be used to locate large bodies of groundwater and zones with anomalous electrical properties. The apparent resistivities measured on the northeast rift zone of La Fournaise volcano can be explained by resistivity distributions involving two extensive electrically distinct zones.

The study area can then be subdivided in two compartments along a limit that coincides with the Bois Blanc E-W cliff. Electrical differences between the two zones cannot only be explained by water content, as different geological contexts have to be considered. As a result, two different hydrogeological behaviours can be distinguished : (i) a typical volcanic "basal" aquifer in equilibrium with seawater and with likely low piezometric level, in the southern zone, and (ii) poorly permeable materials that limit the saltwater intrusion to a littoral belt and contribute to produce perched water bodies, high piezometric heads or both, in the northern zone.

These hydrogeological features are believed to be related to the tectonic evolution of this part of the volcano since the Bois Blanc cliff could be correlated to the remnant north side of a past flank slide.

An important general result of this study is the existence of different coastal hydrogeological zones directly linked to geological subsurface structures, despite a monotonic surface cover of surface lava-flows. That is to say that coastal areas of such young and very permeable volcanic edifices do not solely develop a non-varying groundwater system (low level basal aquifer in equilibrium with seawater). Volcanological substructures may significantly control the groundwater behaviour, and conversely, a previous sufficient knowledge of the volcano-tectonic history of a region is necessary to deal with its hydrogeology.

The second important result is that the subsurface structure of La Fournaise N-E rift zone is characterized to the north of Bois Blanc cliff, by a conductive low-dipping substratum that occurs near 0 MSL. Such a result provides new ideas about the hydrogeology of the area. Deep study drillholes would be helpful to test the validity of our interpretations.

Acknowledgments

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