GEOPHYSICS, VOL. 62, NO. 3 (MAY-JUNE 1997); P. 758–762, 6 FIGS.

Short Note

Audiomagnetotelluric prospecting for groundwater in the Baril coastal area, Piton de la Fournaise Volcano, Reunion Island

Michel Ritz*, Marc Descloitres*, Bernard Robineau‡, and Michel Courteaud‡

INTRODUCTION

Surface geophysics has been used for a number of years to solve a variety of major groundwater exploration problems in coastal and island regions. The electrical properties of near-surface rocks are highly dependent on porosity, degree of saturation, and pore fluid resistivity (Keller and Frischknecht, 1966). Because the resistivity of the formations decreases with increasing salinity of the water content, electrical methods, such as vertical electrical soundings, time-domain electromagnetic soundings, and audiomagnetotellurics (AMT), are well-suited for mapping changes in groundwater salinity and, in particular, for detecting a fresh water-salt water interface.

A multidisciplinary survey was carried out on the south-southwest flank (Baril area) of Piton de la Fournaise Volcano, Reunion Island, to obtain information about water content and water quality. As part of this program, audiomagnetotellurics was employed to determine electrical resistivity stratification with depth, and subsequently to delineate the extent of seawater intrusion in shallow aquifers, where considerable contrasts in salinity might be expected. Using the AMT method (Strangway et al., 1973), scalar measurements of natural electromagnetic signals generated by thunderstorms are used to measure earth resistivity as a function of frequency from which a resistivity-depth relationship may be determined (Vozoff 1972). Interpretation of AMT data depends on the resistivity contrast between rock units, the geometry of the units, and the frequencies used.

GEOLOGY, HYDROLOGY, AND GEOPHYSICS OF THE AREA

Reunion Island (southwestern Indian Ocean) is founded on two shield volcanoes, Piton des Neiges and Piton de la Fournaise. Both volcanoes were built during the last five million years.

Such a shield volcano is built by superposition of long and narrow basaltic flows with low seaward dips. The lava flow is then the potential aquifer unit with high porosity, transmissivity, and anisotropic hydraulic behavior as a result of preferential water flow in scoriaceous beds or lava tubes. Inland, a staged channeled aquifer system ends in the basal aquifer, well known in coastal areas only (Coudray et al., 1990). Thin tuffaceous paleosols and old valley buried detritals (alluvium, lahar) are the main impermeable layers. When reaching the coast, the basal freshwater aquifer has a direct contact with seawater. The two fluids having different viscosities and densities present a concave interface that deepens inland with a gentle 2 to 5% dip (Join, 1991). But diffusion and dispersion generally occur and generate a brackish transition zone, whose thickness depends on the aquifer characteristics. The water system recharge is caused by highland rains, more than 6 m/year above 1200 m altitude, and strong infiltration. Because no permanent river or spring can be used for human purposes, underground water must be located by geophysical methods to increase the success of exploration drillings.

Both direct current and AMT methods have been used on Reunion Island for a variety of problems (e.g., Van Ngoc and Boyer, 1980; Benderitter and Gérard, 1984). Basaltic lava flow resistivity can be summarized as follows: dry flows ranging from 1000 to 8000 Ω-m and freshwater and saltwater-saturated basalt ranging from 100 to 1000 Ω-m and less than 10 Ω-m, respectively. Other low-resistivity formations can be expected such as cinder layers or argilaceous detritals (lahar).

RESULTS

Thirty-four scalar AMT soundings have been collected in the study area (Figure 1) using a SAMTEC 1 instrumentation from IRIS Instruments. The system collects and analyzes two

Manuscript received by the Editor January 23, 1995; revised manuscript received August 15, 1996.
*UR Géophysique appliquée, Centre de Dakar, BP 1386, Dakar, Senegal.
‡Université de la Réunion—Département des Sciences de la Terre, BP 7151, 97715 St-Denis Messag Cedex 9, France.

channels of natural electromagnetic signals in the frequency range of 1 to 7500 Hz.

At some of the sites, soundings were taken with the telluric lines orientated N10°W, N40°W, N65°W and then perpendicular to have azimuthal information, and clarify probable static offset effects in the data. The data available from each site thus consisted of two apparent resistivity and phase curves in each of two perpendicular directions. The sounding data at each site in the six measuring directions were very similar in the band 10 to 7500 Hz. The absence of a consistent polarization direction related to geologic structure suggests that the surficial geologic layers (mainly volcanics) are seen as regionally homogeneous by individual AMT sounding in the study area. Scalar AMT data in the telluric orientations were averaged and standard deviations were computed. Examples of averaged data at sites 17 and 25 are shown in Figure 2. The observed data characteristics indicate that two groups of sounding curves, A and B, can be distinguished by their similar shapes.

Group A apparent resistivity curves (Figure 1) are characterized by an abrupt decrease in resistivity with frequency, without any other prominent feature (for example, results for typical site 25, Figure 2). The corresponding phases have a maximum in the frequency range 100–1000 Hz. Group B apparent resistivity curves also are characterized by a consistent decrease in resistivity (typical site 17, Figure 2) with decreasing frequency, but flattenings of the curves can be observed in the frequency range 100–1000 Hz. Over the same frequency range there is a general minimum in phase.

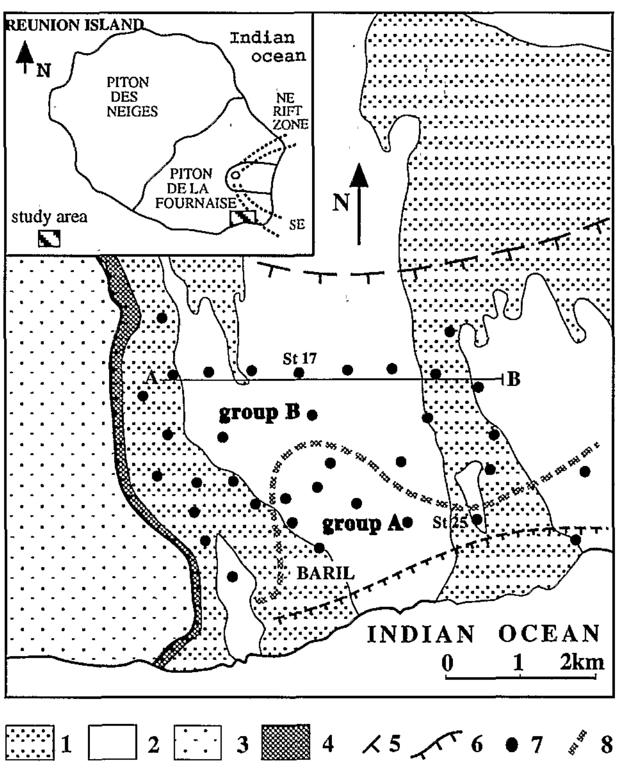

FIG. 1. Geologic map of Baril area (after Bachèlery and Lénat, 1993). AB locates the profile of Figure 4. See text for additional details. 1. Historic lava flows, 2. upper flows of phasis III, 3. lower flows of phasis III, 4. old flows, 5. change in topographic slope, 6. Basse Vallée cliff, 7. AMT sounding, 8. AMT limit between two data groups, A and B.

On the basis of the previous analyzes, we used 1-D modeling to fit the AMT data. The interpretation began with inversion of the observed apparent resistivity and phase data for each site to obtain a 1-D resistivity distribution. Two inversion schemes were used. The first scheme (Jupp and Vozoff, 1975) gives a layered structure, and the second (Constable et al., 1987) provides a solution as a smooth resistivity profile. For the 1-D layered inversion, the data are described adequately by relatively simple two- or three-layer models. Rather than minimizing data-model misfit, the smooth inversion attempts to generate the smoothest model from the data within a specified misfit between observed and model response. Generally, the rms errors between observed and predicted data are between 3 and 12%. Some results of the inversions (layered and smooth) are shown in Figure 3 for typical sites 17 (group B) and 25 (group A). Figure 2 shows an example of the model fit to the data at sites 17 and 25. The responses (not shown) from both layered and smooth models are almost identical.

In a general way, the results of the layered inversion for the group A data indicate a resistive (1000–3000 Ω-m) surface layer 100–300 m thick above a half-space of consistently low resistivities (<10 Ω-m). An exception to this is found near the shore at site 34, where data require a surface layer of about 37 m thick below 100 Ω-m. The interface between the two layers is at various depths below sea level (BSL). Group B models essentially differ from the models of the group A by the existence of a layer of intermediate resistivity (100–600 Ω-m) varying from 250 to 750 m in thickness below the resistive surface layer (1000–5000 Ω-m) 100–700 m thick that overlies the whole of the study area. The thickness of the intermediate resistivity zone increases generally with elevation. The results of the inversions show resistivity variations from the surface to the 100–300 m BSL. Deeper than 100–300 m, all the sites are underlain by a

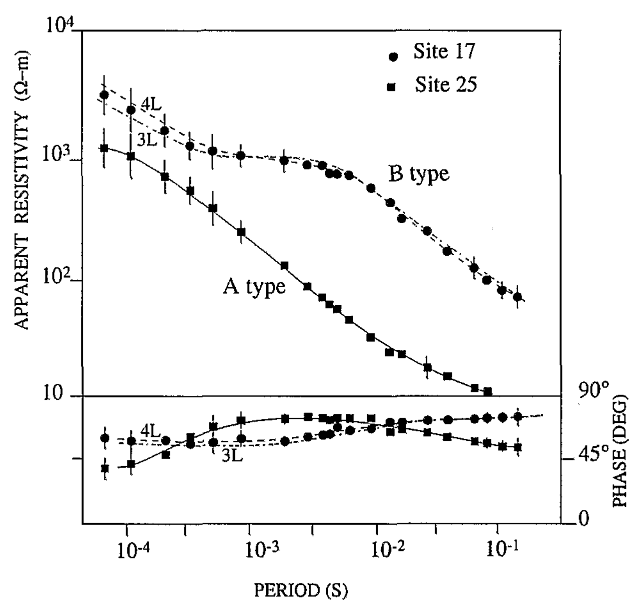

FIG. 2. Typical AMT results at sites 17 and 25 (Figure 1). The continuous and dashed lines are the responses to the models from 1-D inversions. The models are defined in Figure 3. Responses 3L and 4L refer to three- and four-layer models from site 17, respectively. The errors bars in some cases are smaller than the symbol.

low-resistivity layer in the range of 3 to 10 Ω-m. As an example, Figure 4 illustrates an interpreted resistivity-versus-depth cross-section along profile AB (Figure 1) obtained from AMT sounding data.

DISCUSSION AND CONCLUSIONS

The Baril area consists of a great number of metric, subhorizontal lava flows laid one upon another. Vertically or laterally, some other materials can occur, volcanic (tuff, ash) or detritic (paleosol, lahar). These formations are corresponding to successive eruptive and quiet phases. As usual for Hawaii-type volcanoes, nonlava formations are not significant in volume (Bachèlery and Lénat, 1993).

In the survey area, the most important factors affecting the resistivity are rock type (lava or argilaceous) but especially their associate hydraulic characteristics (porosity, permeability, saturation, fluid conductivity). Temperature variations are not a factor in the rock resistivity (Rançon et al., 1989). In addition, the borehole (172 m elevation) cuts rocks with high permeability and porosity to a depth of 380 m, confirming the high permeability of volcanic rocks in Reunion Island.

The lower electrical boundary BSL (Figure 4) that appears to pervade the whole area can probably be attributed to seawater intrusion. The resistivity values beneath the interface are in the range 3 to 10 Ω-m, typical for resistivity of basalts saturated with saltwater. Moreover, the conductor is always seen BSL and deepens systematically landward, which is consistent with the usual behavior of seawater intrusion. The conductive basement thus constitutes a seawater-bearing aquifer. Figure 5 illustrates a contour map of the basement depth BSL. In general, the conductor lies at about 20 m below the coastal sites, while it deepens rapidly to 100–300 m beneath the inland sites; but the deepening is not uniform. The contour patterns indicate a dominant strike that is approximately northwest-southeast of the region mapped, where two anomaly zones A1 and A2 (Figure 5) of significant depth between 150 and 300 m are identified. It will be noted that the northwest-southeast strike is approximately the direction of groundwater flow paths in Baril as interpreted by self-potential measurements (Aubert et al., 1993). This map showing lineations and zonations constitutes (Figure 5) an indirect tool for hydrological and structural qualitative information. The two zones A1 and A2 with deeper conductive basement can be associated with areas of higher hydraulic pressure, and thus represent the sectors with more potential for groundwater resources. The elongation of anomaly A1 suggests a paleo-valley drainage structure. The local high gradient of the inland conductive basement slope (Figure 5) and its associated increasing hydraulic gradient indicate lateral changes in hydraulic characteristics and/or structural influence (Figure 6).

AMT soundings basically indicate three-layered structures with the following units from the surface downward: (1) a resistive cover (100–300 m thick), 1000 to 5000 Ω-m, consisting of recent, probably dry volcanic flows; (2) a transition layer with intermediate resistivity values of 100–600 Ω-m that corresponds to basalts grading downward, from partially to totally saturated with freshwater. The thickness of this layer increases from zero near the coast to about 750 m farther inland; and (3) a very conductive basement having resistivities in the range of 3 to 10 Ω-m and interpreted as being saltwater-saturated basalt.

For Reunion coastal areas, the water table has a maximum few meter extent above sea level, because of the 1 or 2‰ low piezometric gradient (Join, 1991). Thus, it appears that this basal freshwater aquifer is not discriminated within the 100–600 Ω-m thick intermediate layer.

According to the Ghyben-Herzberg principle (Kashef, 1983), the saltwater-saturated basement depth values provide a means of estimating the theoretical position of the water table above sea level. Based on an hydrostatic equilibrium approach, the depth (z) of the freshwater-saltwater interface is a function of the water level above sea level (h) and the fluid densities ratio (i.e., $z = 40\,h$). From the theoretical piezometric surface (between 1 and 6 m above sea level) associated with the brine-saturated basement, attempts to fit the resistivity data by a new

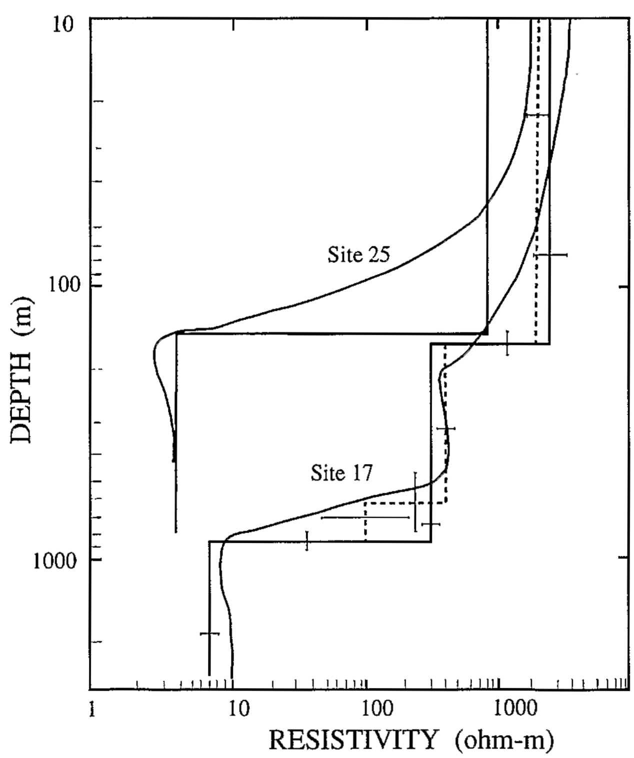

FIG. 3. 1-D layered and smooth inversion results for typical sites 17 and 25. The solid and dash lines are three- and four-layer models for site 17, respectively. Uncertainties on the layer boundaries and estimates of resistivities are 90% confidence limits (not shown when too small, in particular for site 25).

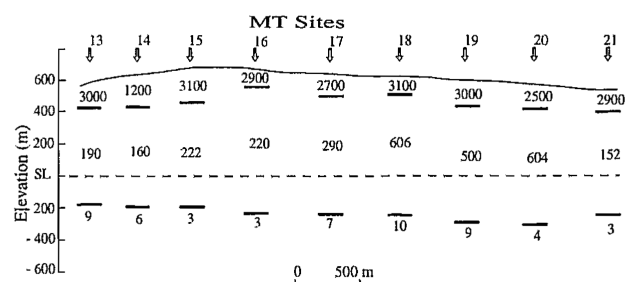

FIG. 4. Single site resistivity models calculated by 1-D inversion for profile AB (Figure 1). Numbers denote resistivity in Ω-m. At the top of the figure, the solid line is the topographical variation at sea level.

three-layer model with a depth at Ghyben-Herzberg's estimate were made. In general, fixing the depth of the top of the intermediate layer at Ghyben-Herzberg's estimate produced a rapid degradation of fit toward high frequencies and an increase in rms error (in excess of 20%). We have then remodeled the data assuming a four-layer case, dividing the intermediate layer into an upper partially saturated layer and a lower totally saturated layer. For example at site 17, we assume an interface at the water table located at a depth of about 6 m above sea level in the intermediate layer. The interpretation (Figure 3) shows that the four-layer model has over a 10 : 1 contrast with the conductive basement and at least a 5 : 1 contrast with layer 2. The four-layer model yields a response (Figure 2), which fits the data with an rms error of 7.8%. The rms error in the fit stayed the same for the three- and four-layer models. We have then investigated how well the physical parameters of resistivity and thickness are resolved (Jupp and Vozoff, 1975). At site 17, the three-layer model parameters are highly defined. The four-layer model parameters are equally resolved but the resistivity and thickness of layer 3 are not well determined (Figure 3).

Although it was not possible to discriminate the basal aquifer electrically, the lower part of the intermediate resistivity layer probably consists of freshwater-saturated materials that constitute the main body of the aquifer. The lower resistivity of the extensive intermediate layer can be explained by one or a combination of several factors: (1) a depth change in fracturation, porosity, and water content; (2) older geologic formations, possibly weathered and argilized; (3) some brackish water above the conductive basement. But the presence of freshwater could be a sufficient reason alone to explain such a resistivity range in a layer mixing freshwater-saturated and wet zones as proposed in Ecker (1976). In this layer, within a complex basaltic environment, a juxtaposition above the water table of saturated, wet or dry compartments cannot be discriminated by our electrical models. We prefer Ecker's hypothesis because of its simplicity and because no argilaceous weathered rocks have been observed along the foot of Basse Vallée Cliff that cuts across older formations.

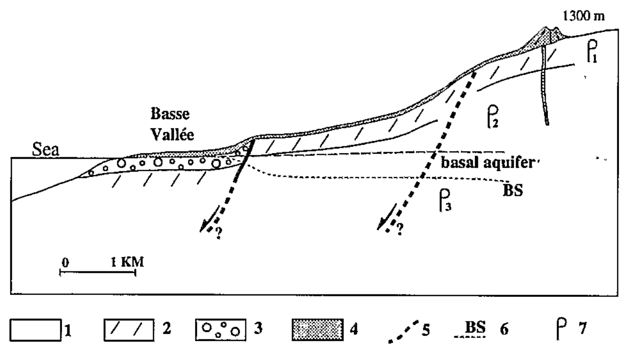

FIG. 6. Interpretative hydrogeologic section across the A1 anomaly. 1. Old weathered lava flow, 2. young flow, 3. detrital deposit, 4. historic cone and flow, 5. slip fault, 6. salt water wedge, 7. resistivity.

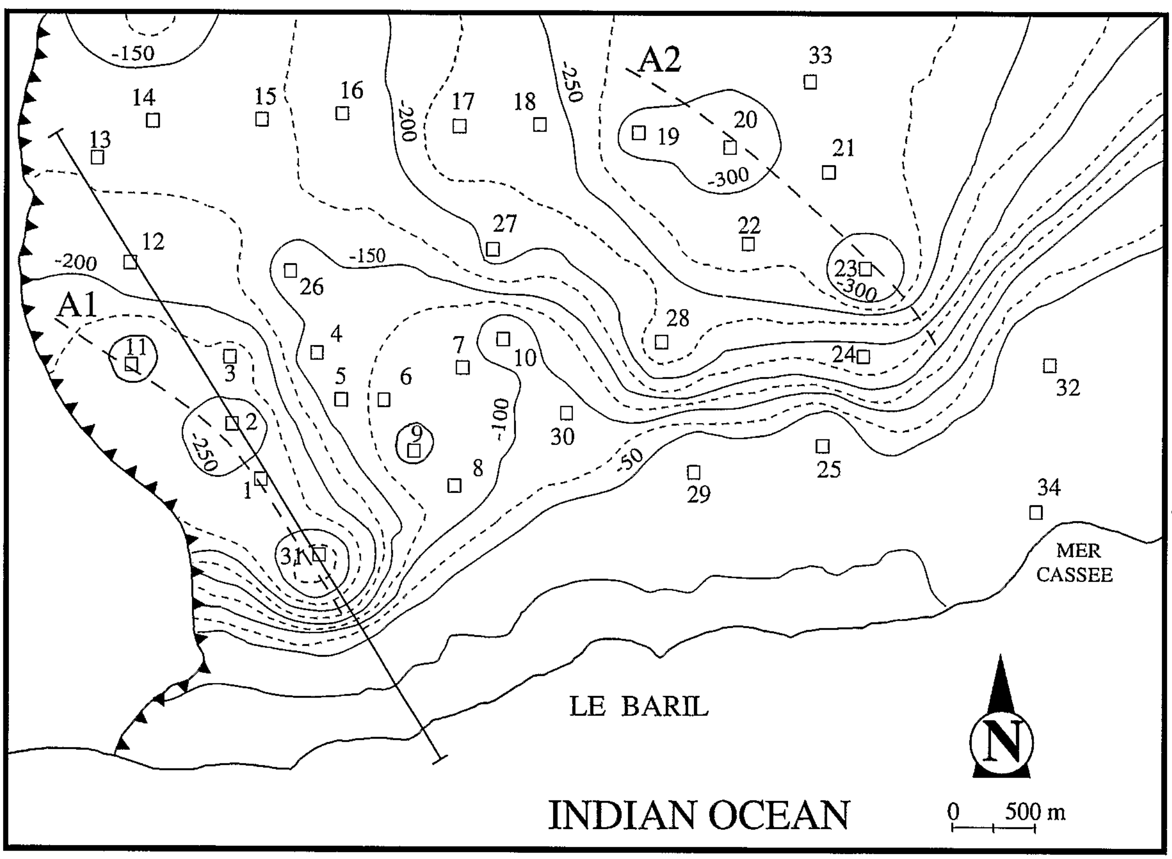

FIG. 5. Contour map of the saltwater-saturated basalt depth BSL in meters. Also shown are the two anomalies A1 and A2 and the location of the hydrogeologic section of Figure 6.

A schematic geologic interpretation of the electrical resistivity structure is proposed in Figure 6, taking into account the available surface geologic data and probable structures in that type of environment. The lower change in the general slope of Baril area is interpreted as a coastal landslide. The foot of this former littoral cliff was then filled by detritic sediments, and recently buried by lava flows issued from the southeastern rift zone (see Figure 1). We suggest that the presence of less permeable sediments represents a local hydraulic barrier to the marine intrusion and allows freshwater to build up along northwest-southeast paleostructures.

The AMT method is found to be feasible for detecting the shallow electrical structure in a volcanic environment, mainly the bottom of the dry basaltic surface flows and the top of the brine-saturated basement. However, none of the soundings were able to discriminate the top of the water table. From AMT data, there is no ready way of detecting the transition from partial to full saturation without benefit of auxiliary information.

ACKNOWLEDGMENTS

This paper is published as part of a groundwater research programme funded by the Conseil Général de la Réunion under Prof. J. Coudray scientific supervising. The authors wish to thank reviewers and the editor for useful comments.

REFERENCES

Aubert, M., Antraygues, P., and Soler, E., 1993, Interprétation des mesures de polarisation spontanée (PS) en hydrogéologie des terrains volcaniques. Hypothèse sur l'existence d'écoulements préférentiels sur le flanc sud du Piton de la Fournaise (île de la Réunion) Bull. Soc. Géol. France, **164**, No. 1, 17–25.

Bachèlery, P., and Lénat, J. F., 1993, Le piton de la Fournaise: Mém. Soc. Géol. France, **163**, 221–229.

Benderitter, Y., and Gérard, A., 1984, Geothermal study of Reunion Island: Audiomagnetotelluric survey: J. Volcanol. Geotherm. Res., **20**, 311–332.

Constable, S. C., Parker, R. L., and Constable, C. G., 1987, Occam's inversion: a practical algorithm for generating smooth models from electromagnetic sounding data: Geophysics, **52**, 289–300.

Coudray, J., Mairine, P., Nicolini, E., and Clerc, J. M., 1990, Approche hydrogéologique: le volcanisme de la Réunion: Tech. Rep., Centre de Recherches Volcanologiques de Clermont Ferrand, France.

Ecker, A., 1976, Groundwater behaviour in Tenerife, volcanic island (Canary Island, Spain): J. Hydrol., **28**, 73–86.

Join, J. L., 1991, Caractérisation hydrogéologique du milieu volcanique insulaire. Le Piton des Neiges, Ile de la Réunion: Thèse doc., Univ. Montpellier II.

Jupp, D. L. B., and Vozoff, K., 1975, Stable iterative methods for the inversion of geophysical data: Geophys. J. Roy. Astr. Soc., **42**, 957–976.

Kashef, A. I., 1983, Harmonizing Ghyben-Herzberg interface with rigorous solutions: Ground Water, **21**, 152–159.

Keller, G. V., and Frischknech, F. C., 1966, Electrical methods in geophysical prospecting: Pergamon Press.

Rançon, J. P., Lerebour, P., and Augé, T., 1989, The Grand Brulé exploration drilling: new data on the deep framework of the Piton de la Fournaise volcano, part 1: lithostratigraphic units and volcano structural implications: J. Volcanol. Geotherm. Res., **36**, 1–3, 113–127.

Strangway, D. W., Swift Jr., C. M., and Holmes, R. C., 1973, The application of audio-frequency magnetotelluric (AMT) to mineral exploration: Geophysics, **38**, 1159–1175.

Van Ngoc, P., and Boyer, D., 1980, Etude des propriétés électriques des zones de risques volcaniques sur le Piton de la Fournaise: Tech. Rep., CNRS-INAG, Paris.

Vozoff, K., 1972, The magnetotelluric method in the exploration of sedimentary basins: Geophysics, **37**, 98–141.