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New geological and hydrogeological implications of the resistivity distribution inferred from audiomagnetotellurics over La Fournaise young shield volcano (Reunion Island)

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Abstract

An audiomagnetotelluric survey has been performed along an inactive flank of La Fournaise volcano massif in Reunion island, to study the subsurface resistivity structure. One-dimensional modelling of the AMT data at each site revealed an extensive low-resistivity (less than 10 Ω m) zone at a few hundred meters below the surface. The significance of this unexpected conductive substratum is discussed in relation with the proposed impact of volcano–tectonic processes (caldera and landslides collapses), and a new interpretation of the geological structure is proposed. Moreover, it is likely that these conductors are poorly permeable argilaceous materials; then they coincide with a limit in permeability and determine groundwater behavior. © 1997 Elsevier Science B.V.

Keywords: La Fournaise volcano; Audiomagnetotellurics; Geoelectric structures; Volcano–tectonic processes; Groundwater; Reunion Island

1. Introduction

Piton de la Fournaise volcano is usually seen as a pile of young (<0.6 MY) and permeable ($10^{-3} < k < 10^{-1}$ m s^{-1}) basaltic lava flows. This expected structure should, as a first approximation, result in a basal groundwater system with very low piezometric gradients and levels. This result is obviously reached by a numerical model of La Fournaise that defines a water level no more than +12 m ASL in the middle of the edifice (Violette, 1993). As a matter of fact, geological and groundwater models seem to be each other related. Is this apparent correlation really satisfactory?

We present a geoelectrical survey (Fig. 1) composed of a profile of eight audiomagnetotelluric (AMT) soundings extending from the Baril area (southern flank of La Fournaise) towards the inner parts of the massif. A one-dimensional (1-D) resistivity model cross section based on our tensor AMT data is proposed. Comparisons with the previous geological and hydrogeological consensual model raise obvious contradictions. Interpretations and hypothesis are proposed for a new geological constitution of La Fournaise and, as an example, for its correlative hydrogeology.

2. Geological and hydrogeological settings

Piton de la Fournaise massif is a typical shield

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volcano constituting the southeastern third part of Reunion island (southwestern Indian Ocean). La Fournaise is characterized by a highly effusive dynamism indicated by the volumic predominance of lavas compared with few pyroclastic formations. Thus, it is considered as built by fast accumulation of basaltic lavas produced mainly at the principal eruptive center and accessorily along two bent northeastern and southeastern rift zones. In this well known volcanological structure (Bachèlery and Mairine, 1990) four volcano–structural units separated by at least three volcano–tectonic events can be distinguished, but the exact nature of these volcano–tectonic discontinuities is still a matter of debate. A first group of authors (Bachèlery and Chevallier, 1982; Bachèlery and Mairine, 1990) consider that the massif is tectonically characterized by the association of summital calderic collapses and lateral flank landslides. A second group (Duffield et al., 1982; Gillot et al., 1994; Lénat and Labazuy, 1990) propose that huge landslides have affected large parts of the massif. More than 500 km^3 of slid materials and debris avalanche deposits, recognized offshore from Grand-Brulé (Fig. 1), appear as a strong argument for huge sliding mechanisms, at least with regard to the last, and unanimously admitted, slide depression of Grand-Brulé.

Nevertheless, despite obvious ''destructive'' volcano–tectonic events, the geological structure of the massif is assumed to be essentially of piled up lava series; crushed or slid materials are always described and considered in the submarine parts of the edifice, as also evidenced by giant gravitational slides discovered offshore several Hawaii islands (Moore et al., 1989). Groundwater resources are mostly provided by boreholes and wells located in the coastal area under 300 m ASL where a continuous water-table is defined as the ''basal aquifer''. This aquifer lies in very permeable volcanic rocks (pumping tests and well specific discharge point to transmissivity values more than 10^{-2} m^2 s^{-1} for penetrations of about 50 m), with low piezometric heads and gradients (from 0.2 to 3.2‰), as revealed by all available drillhole data. Above this altitude, in higher lands, the water level is too deep for groundwater development, and it has never been properly observed. The 145 identified springs are usually interpreted as discharge points of discontinuous aquifers also ranked as so called ''perched water tables''. A numerical model has however been computed for La Fournaise volcano (Violette, 1993). It calculates a water table–reaching a maximum of 12 m ASL in the center of the edifice, on the basis of homogeneous transmissivity distribution compatible with the assumed geological model of young and very permeable lava flows superposition. On the other hand, Join and Coudray (1993) suggest that some highly elevated springs (at altitude somewhat greater than 1000 m ASL) may be in connection with the basal aquifer described in the coastal area.

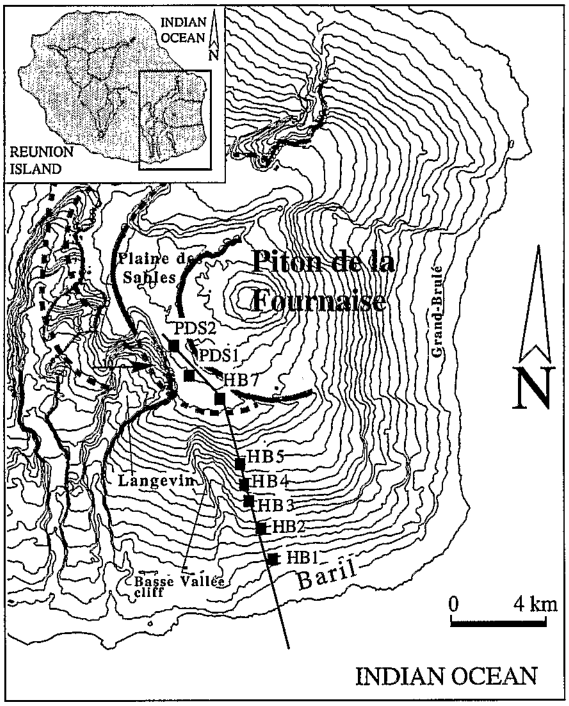

Fig. 1. Topographical map of Piton de la Fournaise massif showing the location of main volcano–tectonic discontinuities (thick dashed or solid lines), and AMT soundings (black squares). Main geographical terms seen in the text are pointed out, as well as the situation of the described geological facies (black arrow). Contour lines are every 100 m.

3. AMT data analysis and interpretation

The AMT survey was designed to provide the gross shallow electrical structure at a scale representative of La Fournaise massif beneath its inactive parts (in terms of eruptivity). Choice for soundings emplacement was seriously hampered by geographical conditions and rugged topography. Nevertheless eight AMT soundings (Fig. 1) have been performed across the Baril planeze (southern flank of La Fournaise massif) towards the inner parts of Plaine des Sables area, and from 200 m to 2300 m elevation. (Note that planeze indicates a large sloping surface constituting a flank-side of a volcano.)

From a structural point of view, a caldera collapse—Sables caldera—occurred between 60 000 and 40 000 years BP (Bachèlery and Chevallier, 1982), marked out by the actual flat area of Plaine des Sables. Three soundings (HB7, PDS1 and PDS2) are a priori located inside this calderic zone. Moreover, a landslide dated less than 94 000 years BP is suspected with its lateral and upper limits being Basse Vallée cliff (Fig. 1) and a change of slope on Baril planeze, respectively (Bachèlery and Mairine, 1990).

The AMT method measures naturally occurring electromagnetic fields over a broad frequency range from 1 Hz to 10 kHz, which are used to give information on resistivity variations with depth (Strangway et al., 1973; Berdichevsky and Dmitriev, 1976). For soundings presented here, all measurements have been made with a tensor Iris Instruments SAMTEC2 system in a frequency band from 1 to 7500 Hz. The data have been analyzed to produce, as a function of frequency at each sounding site, apparent resistivities and phases and E- and H- polarization orientations of the impedance tensor (Vozoff, 1972).

The AMT method may lead to erroneous interpretation if conventional distortion effects as near surface conductivity heterogeneities or topography (Wannamaker et al., 1986; Groom and Bailey, 1989) are not considered. However, topographic effects in AMT (Wannamaker et al., 1986) appear relatively weak if breaks in slope are not large, and the AMT response of the subsurface may be obtained accurately.

Considering our geophysical research program, we have shown (Courteaud et al., 1996) that the topography influence is negligible in both TM and TE modes (maximum resistivity variation less than 10% compared with the true resistivity) except in the immediate vicinity (less than 500 m) of strong breaks in slope or coastal boundaries. Over our study area, soundings were located away from the main break in slope occurring between HB5 and PDS1 sites (Fig. 1) around 1600–2000 m elevation.

The orthogonal AMT sounding curves from most of AMT sites are coincident and reasonably 1-D across the entire observed bandwidth, and they appear to be little affected by static shift. Thus, it seems that the subsurface structure can be regionally approximated by a 1-D isotropic layered-earth model. The determinant AMT response (Ranganayaki, 1984) from the sites free of such shifts is chosen to represent the data.

Note that site HB1 (Fig. 1) could be affected by the ocean (Ogawa, 1987), because closest to the coast (3–4 km). However, for soundings more than 1–2 skin depths from the boundary, the ocean has a minor effect; for site HB1, the skin depth at 20 Hz is about 1200 m assuming the resistivity of 100 Ω m, therefore the effect of the ocean can be neglected; we have already pointed out such a result for previous AMT studies over similar study areas of Piton de La Fournaise volcano (Descloitres et al., 1997).

Examples of data from typical sites HB7 and HB5 (Fig. 1) are shown in Fig. 2. At site HB7 the AMT response is characterized by an abrupt decrease in apparent resistivity with decreasing frequency, without any other prominent feature. This pattern was found for the three AMT soundings located on the upstream part of the profile. For the remaining sites, located on the planeze, a perceptible flattening occurs in the intermediate part of the curve (typical site HB5, Fig. 2), in the frequency range 100–1000 Hz.

The determinant parameters were interpreted by 1-D modelling (Jupp and Vozoff, 1974) with the minimum number of layers that gave a good fit. This typically results in models with two or three layers. The results of this modelling are shown in Fig. 3 as a compilation of the inferred 1-D structures beneath each site. The cross section presented in Fig. 3 reveals a pattern of smoothly varying structures, but discriminates two different geoelectrical sectors: (i) the altitudinal domain shows a resistive surface layer (>1000 Ω m), overlying a low resistivity basement of less than 10 Ω m, (ii) the southern two-third parts of the section present a thick (500–900 m) second layer of moderate resistivity (100–600 Ω m) underlying a resistive (>1000 Ω m) thin surface layer and overlying a conductive basement of less than 10 Ω m.

The transition between these two sectors that corresponds to the major break in slope but also to the supposed location of the paleo-caldera discontinuity (Fig. 1), suggests a structural origin for the geoelectric structures.

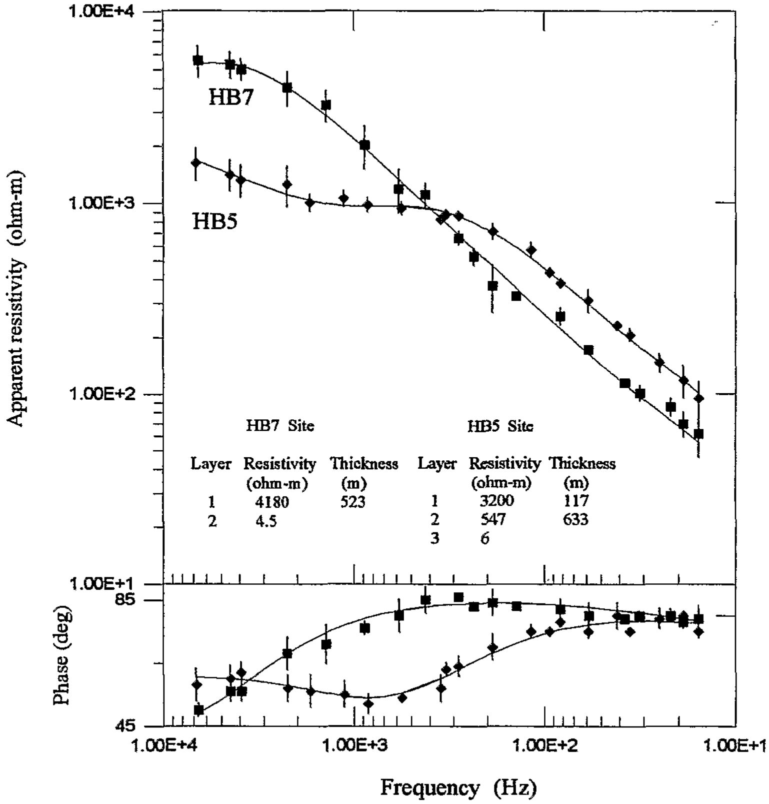

Fig. 2. Examples of determinant apparent resistivity and phase sounding data at typical sites HB5 and HB7 (see Fig. 1) with error bars (95% confidence intervals, not plotted when smaller than the symbols). Solid lines are the responses to the best-fit model from 1-D inversion.

A major fact is the presence of a very conductive basement all over the profile; the depth to this basement is more important for the southern part of the section, but its morphology is especially remarkable for (i) a sub-horizontal pattern in the north, and (ii) an important steady dip downstream along the planeze part of the profile.

The accuracy of our AMT models is difficult to evaluate in the absence of auxiliary data such as well logs or other resistivity information in this region, but because the effect of non-1-D geometry was small, we believe that the results from 1-D models are an accurate representation of the regional resistivity structure of the study area.

4. Discussion and conclusions

Such geoelectrical structures (Fig. 3), characterized by the prominence of conductors at a few hundred meters below the surface, remain in contradiction with the geological and hydrogeological bulk structure usually admitted for La Fournaise volcano, considered as a pile of basaltic, young (<0.6 MY), and permeable ($k \approx 10^{-3}/10^{-1}$ m s^{-1}) lava flows. Because resistivity ranges are relatively well known in similar basaltic edifices (see for example Lienert, 1991), this structure should result in a superposition, from the surface downward, of resistive (dry or unsaturated lavas), moderately resistive (lavas saturated with freshwater) and conductive (saltwater saturated lavas) formations. As a matter of fact, the first resistive (1000–5000 Ω m) layer obtained for all models is typical for dry basaltic rocks; the moderate resistivities (100–600 Ω m) modelled for sites located on the Baril planeze (sites HB2 to HB5) are too low for dry basaltic rocks and can be interpreted in terms of water content in the second layer. Variations in resistivity

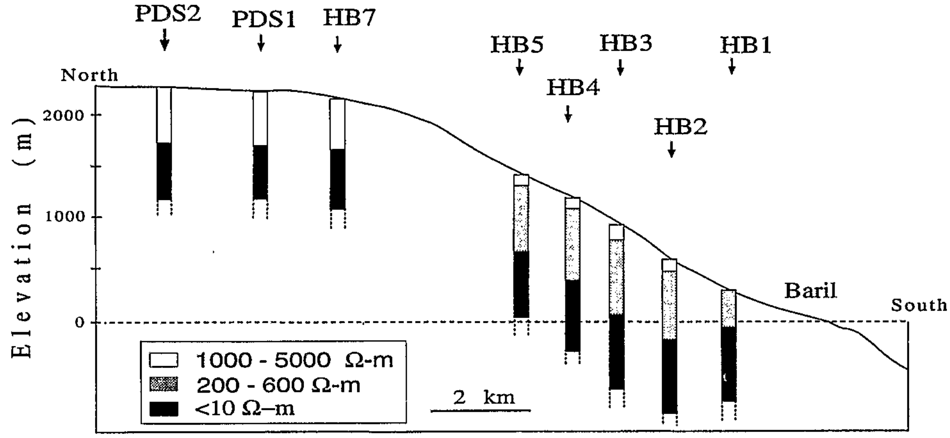

Fig. 3. One-dimensional model cross-section constructed from individual models obtained at each AMT site.

are probably indicative of variations in water saturation and of the relative contribution of clayey interbeds (e.g., paleosoils) in the section. On the other hand, the deep conductive basement of all soundings constitutes, a priori, a surprising fact; further discussion will argue that conventional explanations for conductors in such an environment are inadequate, and will result in new interpretations and assumptions for La Fournaise geological and hydrogeological structures.

4.1. Conventional causes for low resistivities

Despite their apparent disagreement with a young basaltic-lava-built model, conductors are not of unusual occurrence within volcanic edifices, but their relative conventional explanations seem to be poorly convincing in our case. Lahars, ash beds or paleosoils are conductive formations, but such layers are generally thin (metric) and discontinuous on La Fournaise effusive volcano. Occurrence of marine waters cannot be invoked for conductors above sea level, but it is the conveniently fitting interpretation for the conductive basement of site HB1 as shown in recent works (Courteaud et al., 1996). Groundwater is insufficient to generate such low resistivities because measured mineralizations of springs are too low (80 $\mu S\ cm^{-1}$). Temperature is not a credible factor while studied areas are located outside the present eruptive center; indeed, hydrothermalism is not expected as revealed also by low temperatures (16°C) of nearby springs. Nevertheless, hydrothermally altered paleozones could constitute a very convincing argument for large conductors occurrence; this is particularly the case for areas located near ancient eruptive centers, i.e. the Plaine des Sables area (Bachèlery and Mairine, 1990), and for soundings performed straight above (sites HB7, PDS1 and PDS2, Fig. 1). But this explanation is not suited for the sloping conductor modelled below the Baril planeze because of its extension and morphology. However, although the volcanological significance of such omnipresent conductors remains unknown, it certainly should be related to high clay content.

4.2. New hypothesis

Conventional causes seen before to explain low resistivities are more or less related to "constructive" geological processes of La Fournaise volcano, postulated on the prominence of eruptive mechanisms. As an alternative to this prominence we propose a new hypothesis for the conductive basement(s), by considering, within the structure of the massif, a significant amount of detritals. Our idea is enhanced by some geological sections performed on the Langevin river headwall amphitheater (Fig. 1), across formations constituting the still recently hardly accessible left bank of this river, between 1200 and 1400 m elevation. The lower part of all sections are characterized by brecciated materials. Facies observed consist of an unsorted, poorly indurated mixture of pebble- and

Fig. 4. A close up of brecciated materials observed in Rivière Langevin headwall left bank (Fig. 1), showing a mixture of lava clasts in a poorly abundant silty to clayey matrix. The breccia can be correlated to the conductive zone from HB7, PDS1 and PDS2 (Fig. 3).

cobble-size rocks within a poorly abundant matrix silt- to clay-sized. Elements are angular to subangular fragments of olivine or aphyric fresh basalts (Fig. 4). Neither the thickness of the breccia, although more than 200 m, nor the nature of underlying formations can be determined because of field accessibility. Note that lava superposition, and specially hydrothermalized rocks have not been observed there, where this part of Langevin river is close to an ancient eruptive center of La Fournaise and within the Plaine des Sables calderic structure (Fig. 1).

We assume that the clay-rich brecciated materials constitute the subhorizontal conductor modelled for sites HB7, PDS1 and PDS2, since their elevation occurrence can be correlated.

Moreover, we propose a causal effect relationship between brecciated materials and the Plaine des Sables caldera, considering that a lava pile affected by a volcanotectonic event (caldera collapse) have to manifest a resulting part of brecciation, certainly complex and variable, the brecciated facies described above being one occurrence.

Unfortunately, because of the unreachable pattern of its deep geology, no description can be made in order to characterize conductors modelled for sites located on the Baril planeze. Consequently the explanation proposed is speculative, but deals with the same assumption as previously, and takes the advantage to consider the impact of another ''destructive'' volcano–tectonic event: landslides. We interpret the dipping conductive basement of the Baril planeze (Fig. 3) as the top of crushed argilaceous materials produced by a flank slide that has affected this southern part of La Fournaise in its past evolution. The hypothesis of a consequent landslide in this sector is compatible with aerial (Bachèlery and Mairine, 1990) or submarine (Lénat et al., in press) morphological data. Moreover, a similar geoelectrical structure (dipping conductive substratum) have been found (Descloitres et al., 1997) for a comparable profile realized in the Grand-Brulé area (eastern part of La Fournaise) unanimously considered as a recent landslide scar.

4.3. Hydrogeological consequences

Whatever volcanological significance will be given to the conductors, conductive materials are probably correlative of clay-rich formations and so constitute a poorly permeable basement. As a consequence, and

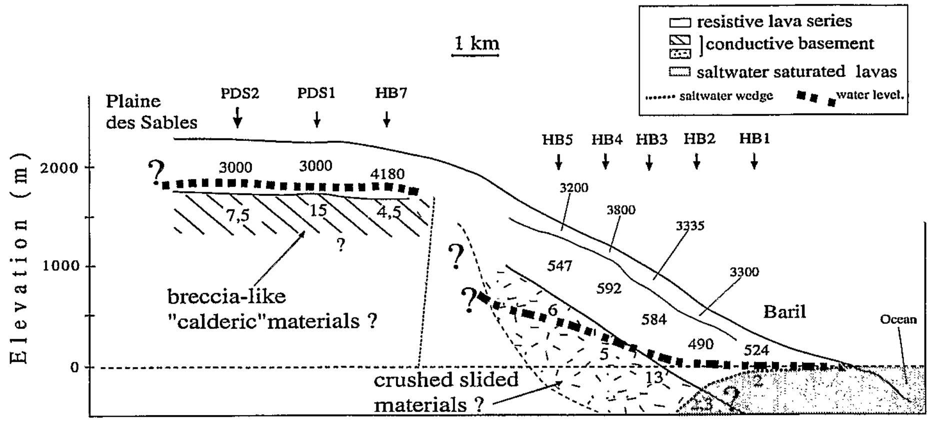

Fig. 5. Proposed geological and hydrogeological interpretive model for the study area based on 1-D AMT inversions (see Fig. 3). Numbers are resistivities in Ω m.

based upon this geoelectrical profile, inactive parts of La Fournaise massif structure appear as a superposition of basaltic lava series, resistive (and permeable), lying on a conductive basement (and poorly permeable) constituting a limit in permeability.

Hydrogeological consequences are major. Good aquifers, developed within the basaltic lava series, could exist at great elevations and controlled by the morphology of the underlying conductive basement. On the other hand, in coastal zones, the occurrence of a poorly permeable basement could constitute a limitation to the landward seawater intrusion, or a sharp increase of the saltwater wedge slope, to say the least. After all, the likely occurrence of poorly permeable conductors reaching great elevations, could result in an associated occurrence of a saturated high level, but poorly productive. The ''basal aquifer'' should not be considered any more as a low landward rising saturated level towards the massif as a whole and should be limited to a littoral belt. This is apparently a common situation in many other volcanic islands where the coastal pervious, low water level, ''basal'' aquifer lies at the foot of a poorly permeable, high water level, island core (Custodio, 1991).

4.4. Conclusions

Fig. 5 shows an interpretive geological and hydrogeological sketch of the geoelectrical section that could be proposed to illustrate the above discussion. Geoelectrical models indicate the aerial extensive prominence of a conductive basement at a few hundred meters below the surface, that do not accredit the assumed ''constructive'' conceptual model of lava flows accumulation. Attempts have been made to show that usual inferences could be inadequate to explain the conductor(s). We have proposed to consider no more the volcano–tectonic events as simple discontinuities, but to consider their impact as the occurrence of destructive originated materials in the bulk structure of the massif. Serious implications in other works that refer to a geological model are expected, and the example of hydrogeology is obvious. Thus such an hypothesis is in the way to a more correlative approach of different disciplines (volcanology, geology, hydrogeology); however, present speculative aspects have to be noted and further works are needed.

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