A conceptual hydrogeological model for a young basaltic shield volcano: Piton de la Fournaise, Reunion Island

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Abstract A magnetotelluric survey in the frequency range 1–7500 Hz, conducted along an inactive flank of La Fournaise volcano massif in Reunion Island, has shown an extensive conductive basement at a few hundred metres below the surface. The significance of this unexpected conductive substratum is discussed in relation to the proposed impact of volcano-tectonic processes (caldera and landslide collapses). It is likely that these conductors are poorly permeable argillaceous materials that coincide with a limit in permeability, and determine groundwater behaviour.

Un modelo hidrogeologico para un joven volcan basaltico: Piton de la Fournaise, Isla de la Reunion

Resumen Una campagna magnetotellurica en la gama de frecuencia 1–7500 Hz, efectuada a lo largo de la ladera inactiva del volcan de la Fournaise en la Isla de la Reunion, revela la presencia continua de un basamento conductor a unas centenas de metros bajo la superficie. La significatión de este substratum conductor inesperado se discute a la luz del impacto posible de procesos volcano-tectonicos conocidos (caldeira, deslizamiento de laderas). Es probable que estos conductores esten constituidos de materiales arcillosos poco permeables. El contraste de permeabilidad asi puestos en evidencia va a determinar el comportamiento de la aguas subterráneas en esta parte del macizo de la Fournaise.

INTRODUCTION

A better understanding of the geology and hydrogeology should be evidently obtained by sufficient drill coverage. But rugged topography, high elevations and deep investigations, make this operation utopian because of the cost. Consequently, indirect methods such as resistivity studies are well suited to yield information on geological and hydrogeological structures. Since electromagnetic methods have proved useful for a number of years in volcanic areas and/or for groundwater purposes (see for example Kauahikaua, 1993), and because of the need of consequent investigation depth, the audiomagnetotelluric (AMT) method appears very attractive in a wide research programme of La Fournaise volcano hydrogeology.

Piton de la Fournaise volcano is usually seen as a pile of young ($<0.6 \times 10^6$ year) and permeable ($T > 10^{-2}$ m^2 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 no more than +12 m a.s.l. in the middle of the edifice (Violette, 1993). As a matter of fact, geological and groundwater models seem to be related to each other. Is this apparent correlation really satisfactory?
soundings extending from the Baril area (southern flank of La Fournaise) towards the inner parts of the massif. Modelled geo-electrical structures, compared to the previous geological and hydrogeological consensual model, raise obvious contradictions. Interpretations and a hypothesis are proposed for a new geological constitution of La Fournaise and its correlative hydrogeology.

LA FOURNAISE MASSIF

Geological setting

Piton de la Fournaise massif is a typical shield volcano constituting the southeastern third part of Reunion Island (southwestern Indian Ocean) which is also grounded by the other inactive volcanic edifice of Piton des Neiges. La Fournaise is characterized by a highly effusive dynamism related to the volume predominance of lavas compared to few pyroclastic formations (Fig. 1). Thus, it is considered to have developed by fast accumulation of basaltic lavas produced mainly at the principal eruptive centre but also along two bent northeastern and southeastern rift zones. Its well known volcanic structure (Bachèlery & Mairine, 1990) distinguishes four volcano-structural units separated by at least three volcano-tectonic events, the exact nature of which is still a matter of debate. A first group of authors (Chevallier & Bachèlery, 1982; Bachèlery & Mairine, 1990) consider that the massif is tectonically characterized by the association of caldera summit collapses and lateral huge flank landslides. A second group (Duffield *et al.*, 1982; Gillot *et al.*, 1994; Lenat & Labazuy, 1990) propose that huge landslides have affected large parts of the massif. More than 500 km^3 of slide materials and debris avalanche deposits recognized offshore from Grand-Brulé (Lenat & Labazuy, 1990) 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 slide 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).

Hydrological pattern

The groundwater flow pattern of La Fournaise volcano is still a matter of discussion. Lack of hydrogeological information in the highlands is the main reason for misunderstanding. Nevertheless, the available studies have shown the main hydrological characteristics of the volcano.

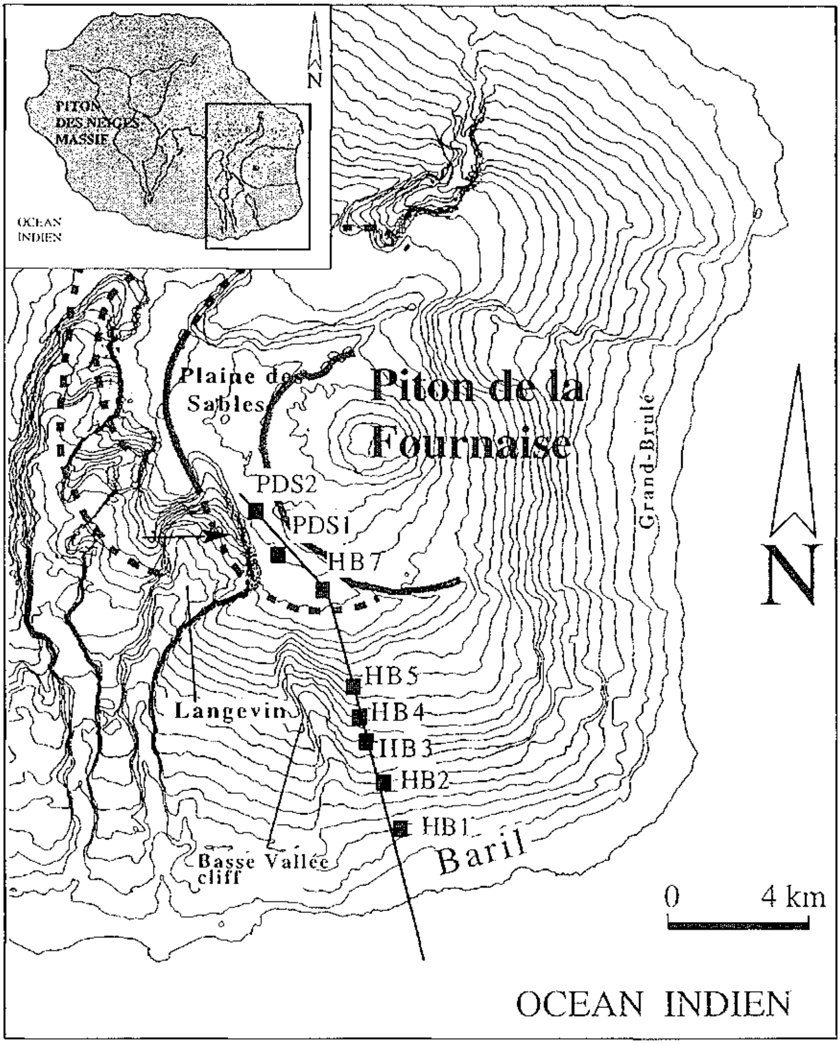

Fig. 1 Topographical map of Piton de la Fournaise massif showing the location of the main volcano-tectonic discontinuities (thick dashed or solid lines), and AMT soundings (black squares). The main geographical terms referred to in the text are pointed out, as well as the situation of the geological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

Groundwater recharge is important, due to heavy rainfalls from tropical depressions and cyclones. Total feeding potential (infiltration + runoff) has been estimated at 3850 mm year^{-1} (Gourgand & Stieltjes, 1988). Groundwater resources are mostly provided by boreholes and wells located in the coastal area under 300 m a.s.l.. In this area, investigations have shown the presence of a continuous water table defined as the "basal aquifer". This aquifer lies in very permeable ($T > 10^{-2}$ m^2 s^{-1}) volcanic rocks with low piezometric heads and gradients (0.2–3.2), 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

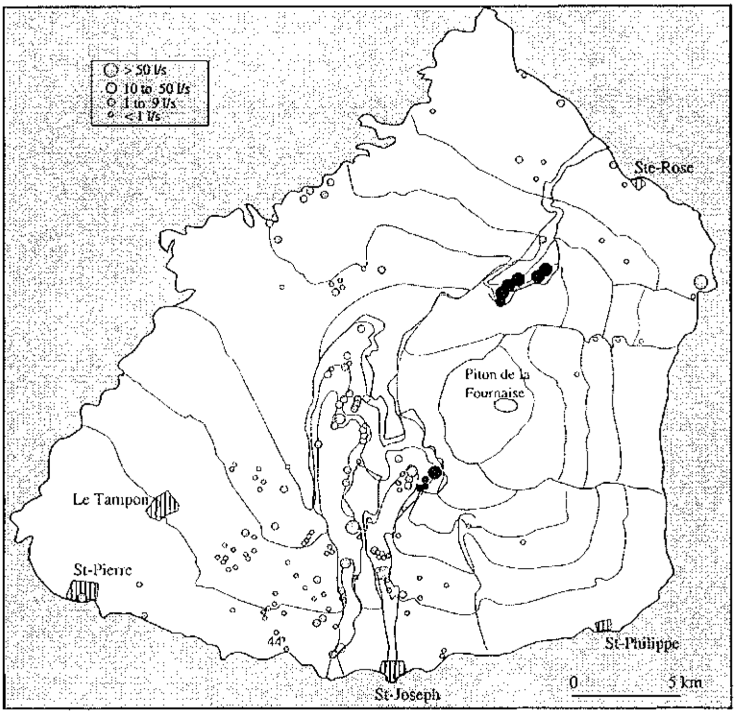

Fig. 2 145 springs identified on La Fournaise massif. Black circles represent very copious springs (>50% of total occurring spring discharge) located at high elevation in central parts of the massif.

properly observed. The 145 identified springs (Fig. 2) are usually interpreted as discharge points of discrete aquifers (Gourgand & Stieltjes, 1988) also ranked as so-called "perched water tables". A numerical model has however been computerized for La Fournaise volcano (Violette, 1993). It calculates a water table reaching a maximum of 12 m a.s.l. in the centre 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 (1991), on the basis of a hydrochemical study, suggests that some highly elevated springs (at altitude somewhat greater than 1000 m a.s.l.), may be in connection with the basal aquifer described in the coastal area.

AUDIOMAGNETOTELLURIC (AMT) PROSPECTING AND RESULTS

Prospecting area

The main objective of AMT prospecting is to provide subsurface geo-electrical structures 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 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 200–2300 m elevation.

From a structural point of view, a caldera collapse—Sables caldera—occurred between 60 000 and 40 000 years BP (Bachèlery & Chevallier, 1982). It is 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 Basse Vallée cliff (Fig. 1) and a change of slope on Baril planeze (Bachèlery & Mairine, 1990).

AMT results

The AMT method measures naturally occuring electromagnetic fields over a broad frequency range from 1 Hz to 10 kHz, which are used to give information on resistivity variations with depth (Vozoff, 1972). For the soundings presented, all measurements have been made with a tensor Iris Instruments SAMTEC2 system. The data from this study have been analysed to produce, as a function of frequency at each sounding site, apparent resistivities and phases and the directions of the principal axes of the impedance tensor. In general, the small deviations between the principal apparent resistivities observed for AMT soundings, across the entire bandwidth, indicate that, in a first approximation, a one-dimensional model of the sounding curves can be considered. In Fig. 3 the principal apparent resistivity and phase values at typical sites HB7 and HB4 (Fig. 1) are shown. The AMT response observed at site HB7 is characterized by an abrupt decrease in resistivity with frequency, without any other prominent feature. This characteristic 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 in the intermediate part of the curve occurs (for example typical site HB4), in the range 100–1000 Hz, and for apparent resistivity values of 700–1000 Ω m. One-dimensional modelling (Jupp & Vozoff, 1974) of the sounding curves result in conventional two-layer models (for soundings similar to typical site HB7, Fig. 3), and three-layer models for other sites. The electrical layering interpreted from AMT soundings shows a good consistency from site to site. The cross-section presented in Fig. 4 reveals a pattern of smoothly varying structures, but discriminates two different geo-electrical sectors: (a) the altitudinal domain located soundings show a resistive surface layer (>1000 Ω m), overlying a low resistivity basement of less than 10 Ω m; and (b) the southern two-thirds of the section present a thick (500–900 m) second layer of moderate resistivity (100–600 Ω m) underlying a poorly thick resistive (>1000 Ω m) 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 palaeo-caldera discontinuity (Fig. 1), suggests a structural origin for the geo-electrical structures.

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 (a) a sub-horizontal pattern in the north and (b) an important steady dip downstream along the planeze part of the profile.

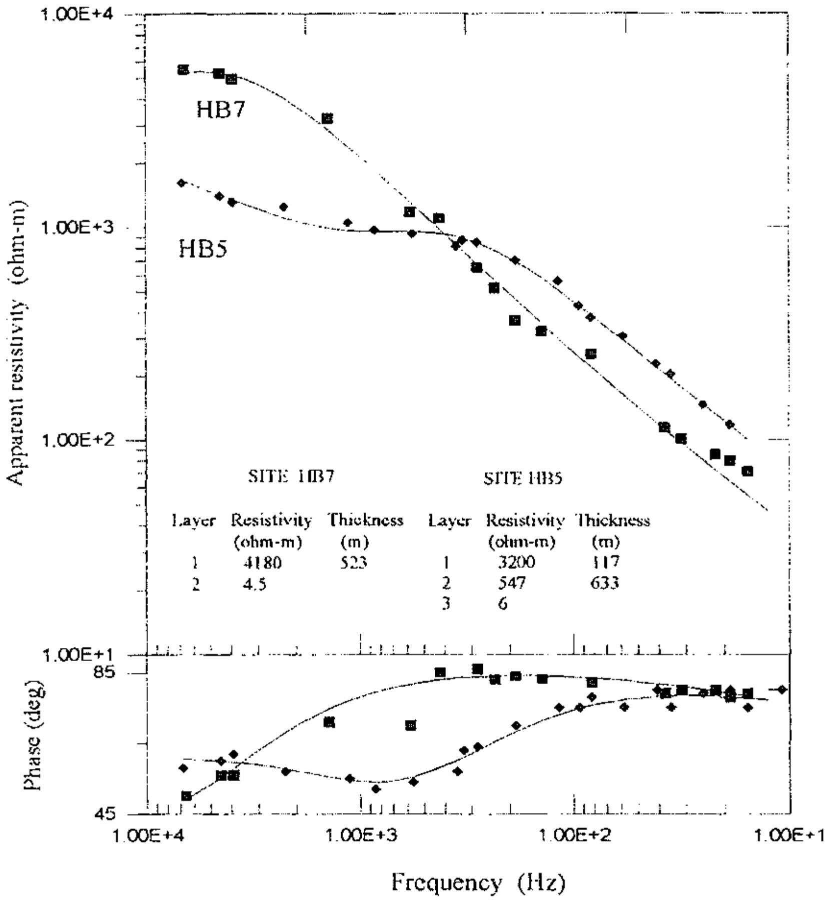

Fig. 3 Examples of determinant apparent resistivity and phase sounding data at typical sites HB5 and HB7 (see Fig. 1). Solid lines show the responses to the best-fit model from one-dimensional inversion.

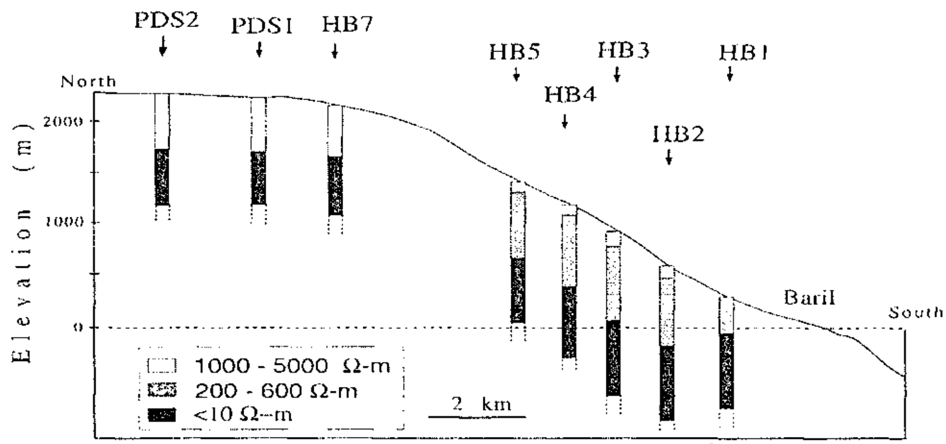

Fig. 4 Composite one-dimensional geo-electrical cross-section using AMT data.

INTERPRETATION AND DISCUSSION

The aim of this section is to propose explanations and a hypothesis for the resistivity distributions shown in Fig. 4. Such geo-electrical structures, characterized by the prominence of conductors at a few hundred metres below the surface, remain in contradiction with the geological and hydrogeological bulk structure usually admitted for La Fournaise volcano. 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 under the freshwater level) and conductive (saltwater saturated lava) 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 plancze (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 are probably indicative of variations in water saturation and of the relative contribution of clayey interbeds (e.g. palaeosoils) 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.

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 palaeosoils are conductive formations, but such layers are generally thin 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 mineralization of springs is too low (80 μS cm^{-1}). Temperature is not a credible factor while studied areas are located outside the present eruptive centre; indeed, hydrothermalism is not expected as revealed also by low temperatures (16°C) of nearby springs.

Nevertheless, hydrothermally altered palaeozones could constitute a very convincing argument for large conductors occurrence; this is particularly the case for areas located near the ancient eruptive centre, i.e. the Plaine des Sables area (Bachèlery & Mairine, 1990), and for soundings performed directly above it (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 volcanic significance of such omnipresent conductors remains unknown, it certainly should be related to high clay content.

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 amphitheatre (Fig. 1), across formations constituting the, till 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 cobble-size rocks within a poorly abundant matrix of silt- to clay-sized material. Elements are angular to sub-angular fragments of olivine or aphyric fresh basalt.

Although more than 200 m, the thickness of the breccia cannot be determined because of field accessibility; nor can the nature of underlying formations. 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 centre of La Fournaise and within the Plaine des Sables calderic structure (Fig. 1). We assume that the clay-rich brecciated materials constitute the sub-horizontal 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 volcano-tectonic 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. 4) as the top of crushed argillaceous 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 aereal (Bachèlery & Mairine, 1990) or submarine (Lénat *et al.*, in press) morphological data. Moreover, a similar geo-electrical structure (dipping conductive substratum) have been found (Descloitres *et al.*, in press) for a comparable profile realized in the Grand-Brulé area (eastern part of La Fournaise) unanimously considered as a recent landslide scar.

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 based upon this geo-electrical 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. Very productive aquifers, developed within the basaltic lava series, could exist at great elevations and be controlled by the morphology of the underlying conductive basement. Copious springs observed in the central high parts of the massif (Fig. 2) could be related to such aquifers. 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 aquifer. The "basal aquifer" should no longer be considered as a low landward rising saturated level towards the massif as a whole. This conception merges to the groundwater circulation model proposed by Join & Coudray (1993), in which the basal aquifer level can reach an altitude greater than 1000 m a.s.l. under its submittal part. Figure 5 shows an interpretative geological and hydrogeological sketch of the geo-electrical section that could be proposed to illustrate the above discussion.

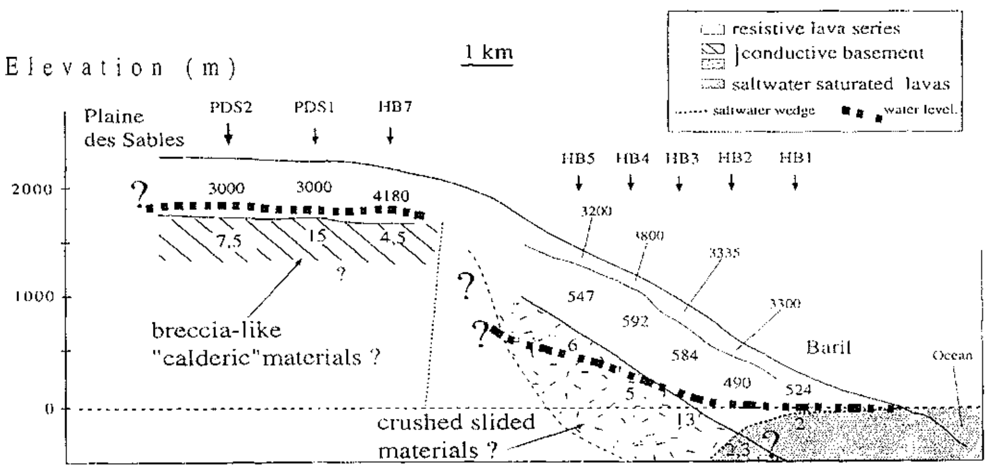

Fig. 5 Interpretative geology and hydrogeology proposed for the geo-electrical section issued from AMT data (see Fig. 4). Numbers are resistivities in Ω m.

CONCLUSIONS

The results of this magnetotelluric survey show the resistivity distribution with depth, for a profile representative of an inactive flank of La Fournaise volcano, from a coastal area towards central parts of the massif. Geo-electrical models indicate the areal extensive prominence of a conductive basement at a few hundred metres 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), and, as an hypothesis, we have proposed consideration of a new geological scheme taking into account the impact of "destructive" volcano-tectonic events as the occurrence of destructive originated materials in the bulk structure of the massif. Such an hypothesis is speculative and further work is needed. However, these conductors can be associated to poorly permeable formations that constitute a limit in permeability. The major hydrogeological consequence is the resulting possible occurrence of inland high elevation water levels, and the limitation of the so-called "basal aquifer" 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, densely dyke injected, island core (Custodio, 1991).

However, this paper that emphasizes a particular explanation for low permeability cores (i.e. the role and impact of volcano-tectonic events) deals with a more structural control on groundwater behaviour; thus, because volcano-tectonic events affect locally-defined parts of La Fournaise volcano, this could result in a possible hydrogeological geographical differentiation of the young massif.

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