Electrical structure of Plaine des Sables caldera, Piton de la Fournaise volcano (Reunion Island)

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Abstract
An Audio Magnetotelluric (AMT) profile has been carried out across the Plaine des Sables, a former caldera of the active Piton de la Fournaise volcano, Reunion Island. Located in the Western Indian Ocean, between the Mascarene and Madagascar basins, this basaltic shield volcano originates from the activity of a hot spot. Our aim was to determine the internal structure of the volcano, in particular the shallow electrical properties of an area extending between the old and the new caldera rims. Although several teams had already conducted AMT work in this region a few years ago, there was a need for more a detailed, in depth survey. Our final model displays a noticeable slope of the Plaine des Sables basement oriented toward the present Fournaise summit. This slope is interpreted as resulting from successive landslides toward the ocean. We conclude that this dipping, electrically good conducting layer, probably belongs to the flat layering of an older caldera.

Key words *magnetotellurics – Piton de la Fournaise – volcanoes*

1. Introduction

The volcanic activity observed at Reunion Island results from the presence of a hotspot (Morgan, 1981). Piton de la Fournaise is the active basaltic shield volcano of Reunion Island, built upon the south-east slopes of the much larger Piton des Neiges volcano, at a distance of about 30 km. The latter is an extinct volcano that reaches its highest point of 3070 m 10 km to the NW of the island center. Piton de la Fournaise activity has moved a distance as large as 8 km to the south-east over the last 0.53 m/yr (Gillot and Nativel, 1982; Rivals 1989). This period appears to be the age of the oldest lavas attributed to Piton de la Fournaise. The volcano has left behind the imprints of two ancient, concentric caldera rims (fig. 1): Rivière des Remparts (0.527-0.290 m/yr B.P., a period known as Phase I of the volcano) and Rempart des Sables (0.219-0.041 m/yr B.P., Phase II). In fact, it has generally been accepted that the volcano's history could be classified into four eruptive phases (Kieffer, 1990). Each volcanic phase ended with the collapse of the edifice, leading to the appearance of a caldera. The 5000 year old Enclos Fouqué (Phase III) is the youngest of three calderas which are nested into each other (0.019-0.005 m/yr B.P.). The terminal cone of Fournaise (Phase IV) towers above the middle of this caldera at an elevation of 2632 m (< 5000 years B.P.).

Our predecessors (Barthes *et al.*, 1984; Benderitter, 1984) established the presence of electrically good conducting layers embedded in the high-resistive basalts. These conductors were detected at all magnetotelluric sounding sites on the island, and among others in the

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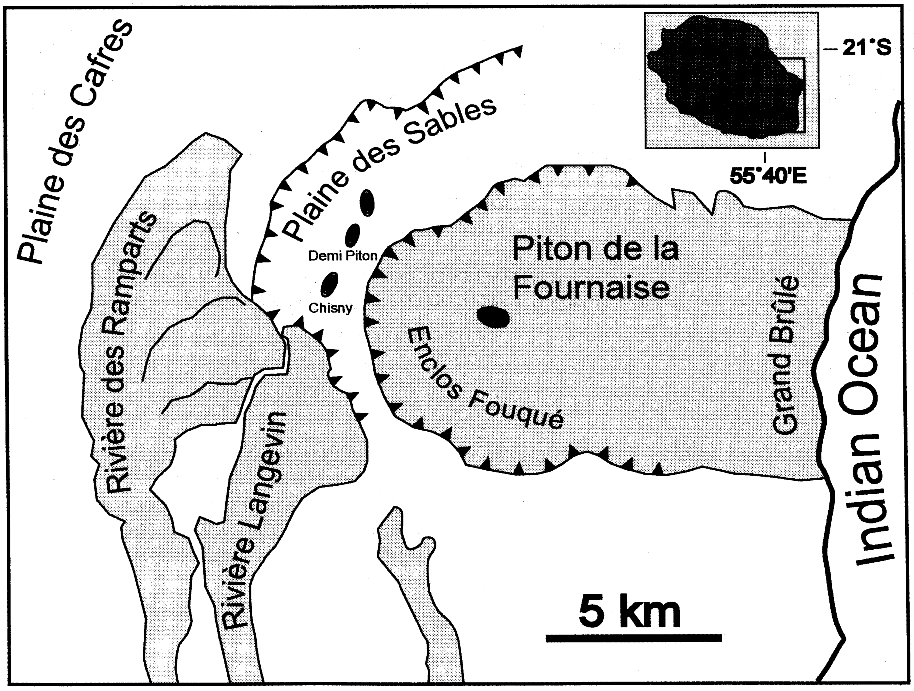

Fig. 1. Regional map showing the location of the Piton de la Fournaise volcano, the rims of Caldera II (Plaine des Sables) and III (Enclos Fouqué), and the troughs of Rivière des Ramparts and Rivière Langevin.

Fournaise area. In the present work, we study the depth distribution of these conducting layers to elucidate the structures of geological interest, taking advantage of the exceptionally high resistivity contrast displayed by these rocks. Note that 1D magnetotellurics excels in determining the depth to conducting layers embedded in the resistive matrix. Some volcanologic problems related to the thickness of more recent sediments can be tracked accurately under these favourable conditions. An example of such problems is the determination of the depth to the contacts of the various volcanic phases, of utmost relevance for the understanding of the volcano's history.

However, because of the large screening effect of high conducting layers at AMT frequencies (greater than a few Hz) and the moderate conductivity of magma (0.2 S/m), no attempt was made to detect the presence of magmatic chambers.

2. Geology of Piton de la Fournaise

The Plaine des Sables is a 2 × 3 km trough which makes up the western part of Caldera II, exhibiting a perfectly flat area at an elevation of 2260 m. This flat cover results from the recent filling by abundant, light, pyroclastic lapilli emitted by a neighbouring small crater, Piton Chisny (southernmost «piton», fig. 1). The caldera floor itself results from lava flows which have occurred during Phase III. Chisny is one of a few secondary craters cropping out along a fissure running parallel to the Caldera III rim, at a distance of 1000 m (Kieffer, 1990).

Enclos Fouqué (Caldera III) is breached on the east. Under the action of vertical collapses and lateral landslides it connects to the ocean with an 8 km wide downfaulted trough (Bachèlery and Mairine, 1990). Plaine des Sables (Caldera II) is likely to behave the same way. Its continuation toward the ocean can actually be observed on the coast (Bachèlery, 1981). These observations suggest that the landslide mechanism produced noticeable effects. They support the much debated theory of Duffield *et al.* (1980) who argue that the caldera nesting results from easterly migration of the focus of volcanic activity, with the nested faults approximately marking the loci of pre-existing rift zones. However, Bachèlery and Mairine (1990) object that traces of these paleo-rift zones are not visible in the Rivière des Ramparts, a neighbouring 1100 m-deep canyon.

3. Expected benefits from the MT technique

By their masking action, the alternation of lava flow, pyroclastic ash deposits, subsequent collapses and erosion have left many structural questions unresolved, such as the geometry and depth of the Plaine des Sables basement, and the throw associated with the collapse that produced Caldera II. To investigate such shallow electrical structures we carried out a profile of Audio Magnetotelluric (AMT) soundings. This technique has been applied several times on the island, with variable success however due to extreme topographic effects and poor ground-electrode contact. The most noticeable result was the discovery of a ubiquitous, shallow conductive layer at hectometric depth (Barthes *et al.*, 1984; Benderitter, 1984). In 1985, a borehole drilled in the Grand Brûlé zone (eastern slopes of Piton de la Fournaise) (Rançon, 1990) (fig. 1) revealed the presence of clay horizons at depths between 440 and 550 m from the surface. The origin of clay build-up is well understood: it results from the hydrothermal alteration of basalt. Because clay is a fairly good electrical conductor due to a high ionic content, Benderitter (1990) suggested using clay deposits as a marker for mapping the topography of buried volcanic features that have experienced hydrothermal alteration. Benderitter suggested mapping the newly discovered «proto-Fournaise», an older volcanic edifice buried beneath the current oceanic coast, at the east of today's Piton de la Fournaise. This particular sounding may prove difficult to carry out, however, owing to the masking effect of nearby, highly conductive sea water.

Considering the numerous, statistically representative AMT results obtained by the present author (western profile, see next section) and his predecessors (Barthes *et al.*, 1984; Benderitter, 1984, 1990) at various sites located in areas older than Phase III of Fournaise, it is observed that the depth to the top of the clay layer varies between 200 to 500 m. Greater depths have not been reported for such old areas. Consequently when, at newer sites, the AMT modelling gives a thickness of the resistive cover in excess of 500 m, it is likely that sediments have settled there in a time too recent for the hydrothermal process to have run its course completely. This agrees with Benderitter (1984) who observed that the thickness of the high-resistivity rocks increases from the coast toward the Fournaise summit, where the youngest basalts are found.

In the present work, we apply these observations to the electrical study of the Plaine des Sables basement.

4. Magnetotelluric soundings

The AMT results shown in this paper are in the high frequency section of a wide-band Magnetotelluric (MT) survey of the Piton de la Fournaise volcano. Unfortunately, most of the long period data (8-0.001 Hz) were of poor quality owing to very small geomagnetic activity at the time of the survey. The AMT band used in this study is bounded at high frequency (200 Hz) by the noise of the magnetic coils (three ECA CM-11) and at low frequency (8 Hz) by the lack of AMT signal below the Schumann resonances. However, the large skin depth of AMT frequencies over basaltic rocks allows us to reach conductive targets at depths in excess of 3 to 5 km.

On a profile slightly longer than 1 km, extending eastward between the rims of Calderas II and III, 12 tensor-AMT soundings were carried out along the road which crosses the

Plaine des Sables (fig. 2). Three soundings (24, 25, 26) were repeated to improve the low data quality at sites 17, 18 and 19 and the latter are therefore not drawn on the map. Another set of 11 sites have been sounded downhill between Caldera II rim and Plaine des Cafres, the main valley located at the saddle ridge half-way to Piton des Neiges. Note that the westernmost station (site 11) is not used, due to insufficient data quality.

Our magnetotelluric system has been described elsewhere (Schnegg *et al.*, 1987). Because low-frequency signal quality was good enough at site 14, we used the full spectrum (200-0.001 Hz) recorded at that site to estimate the thickness of the conductive, shallow layer. However, because of very low geomagnetic activity during this winter's field campaign (August 1994) at low latitude (21°S), no data was available in the 8 Hz-5 s band, even at that site.

Figures 3a,b show the apparent resistivity and phase for the two polarisations as functions of the signal period, obtained on both profiles after rotation of the magnetotelluric impedance matrix into the major and minor

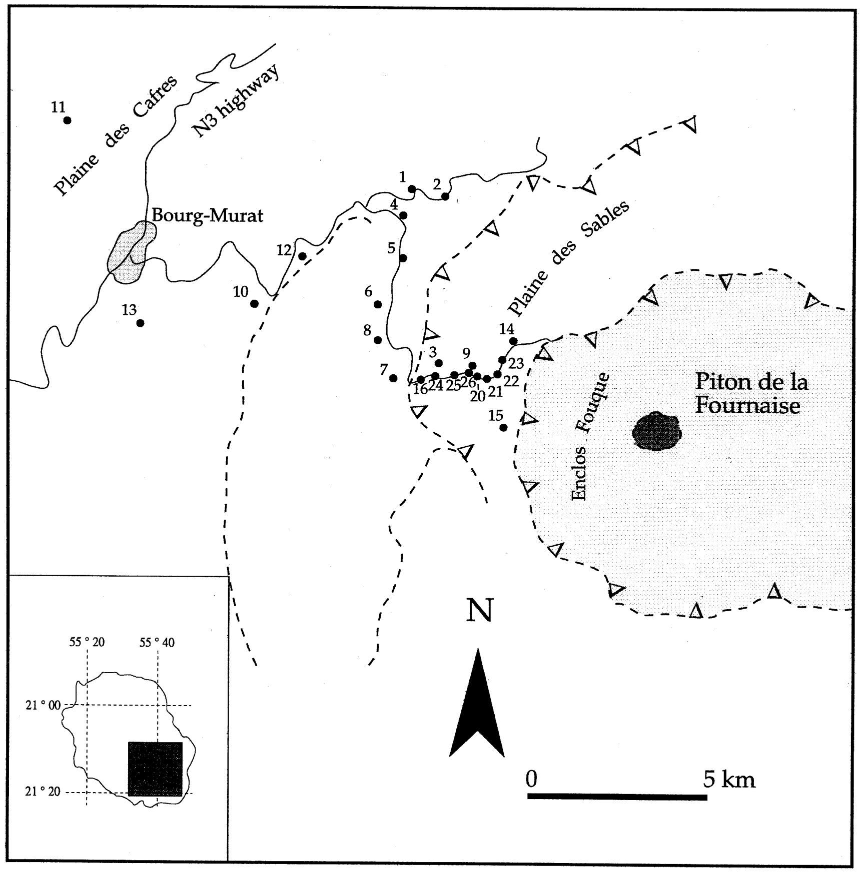

Fig. 2. Geographic location of the 23 sounding sites. Most of them are along the road (solid line) crossing the Plaine des Sables Caldera II. Dashed lines represent fault scarps (edges of Calderas II and III), and the edges of the main troughs.

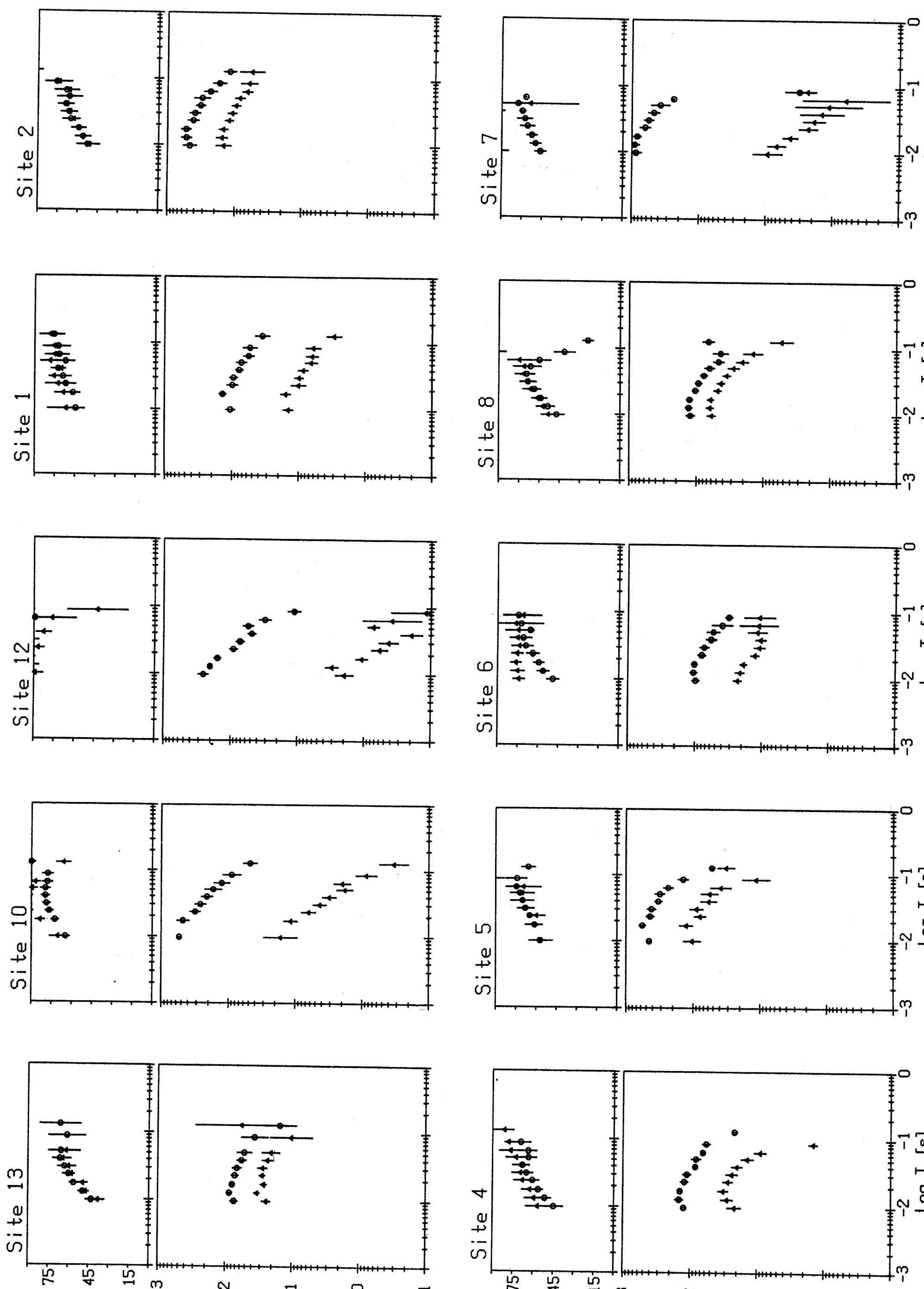

Fig. 3a. Major (o) and minor (▲) MT apparent resistivities and phases at 10 sites outside Plaine des Sables caldera as functions of the signal period *T*.

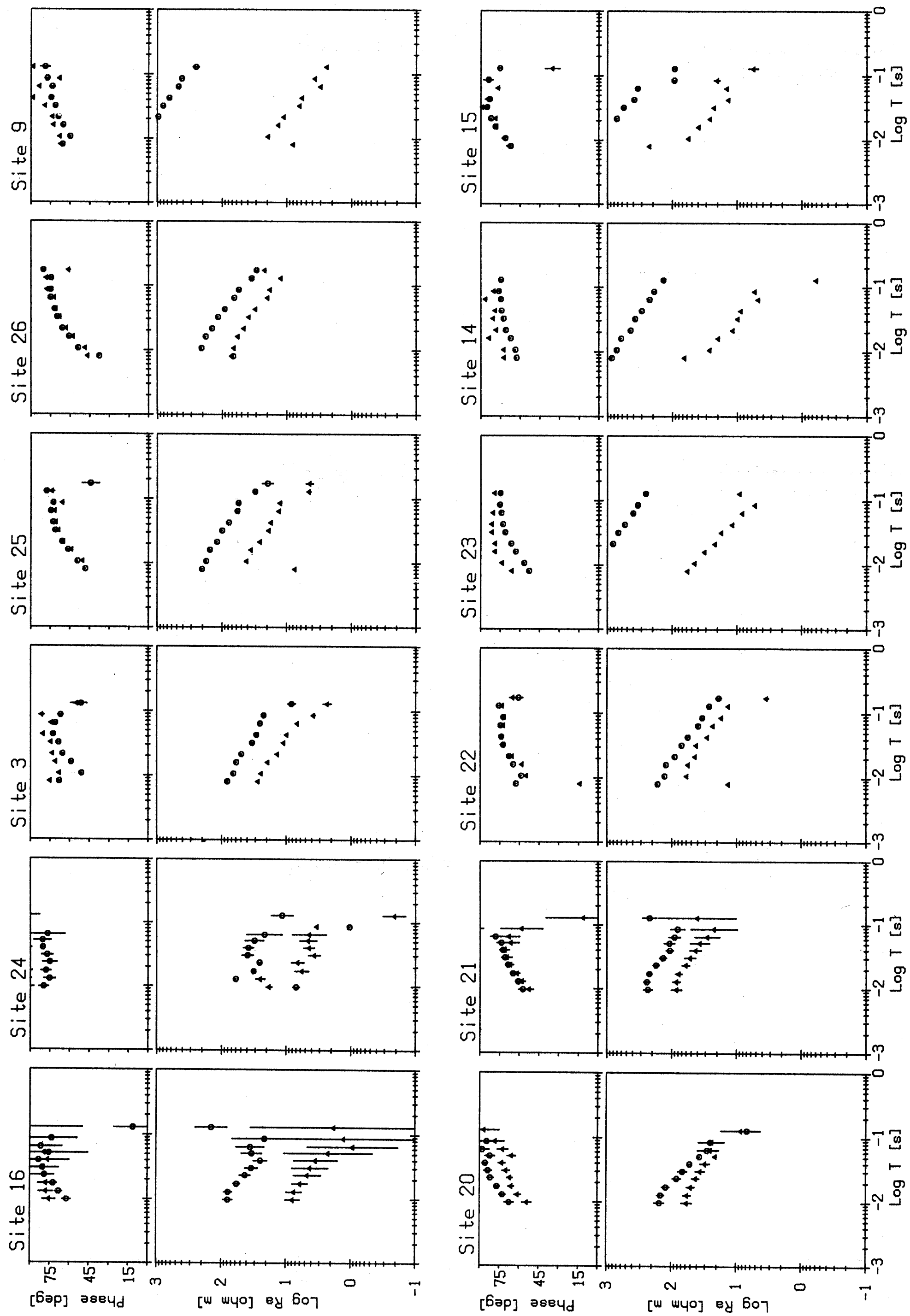

Fig. 3b. Major (o) and minor (▲) MT apparent resistivities and phases at 12 sites inside Plaine des Sables caldera as functions of the signal period *T*.

axes. Figure 4 shows the direction of major axes. Arrow lengths are proportional to the anisotropy amplitude, defined as $|\log_{10}(\rho_{max}) - \log_{10}(\rho_{min})|$, where ρ_{max} and ρ_{min} are the major and minor apparent resistivities. Obviously, a full spectrum of anisotropic behaviour can be observed. They range from almost 1D (sites 8, 20, 22) to highly anisotropic (sites 5, 9, 12). At several sites, topography is clearly responsible for the high degree of anisotropy. Sites 4, 5, 7, 12, 15, 16 and 24, for instance, are within 400 m of the caldera cliff. This almost vertical topography forces the electric currents that flow perpendicularly to the cliff to plunge, but leaves the parallel currents undisturbed. This is the effect that makes the MT tensor anisotropic. But at other anisotropic stations (9, 10, 14, 23), there is no particular unevenness of the ground. For instance, in spite of the flat, undisturbed appearance of the Plaine des Sables basin, we measure a very large resistivity anisotropy at site 9. This fact may suggest the hidden presence of a shallow basaltic body related to the small neighbouring craters, buried away in the pyroclastic lapilli emitted by Piton Chisny. Other sites (14, 23) clearly owe their anisotropy to the nearby Demi Piton crater (fig. 1).

A 2D modelling of an MT profile only makes good sense when all axes are similarly oriented toward a fixed direction (modulo 90°) at all sites. Obviously, this is not the case in our survey, as seen on fig. 4, owing to various sources of electrical anisotropy. It was therefore chosen to model the data set with a 1D algorithm (Fischer and Le Quang, 1981). The experimental data used was the main invariant of the MT response $I = 1/2\,(Z_{xy} - Z_{yx})$, where Z_{xy} and Z_{yx} refer to the major and minor elements of the impedance matrix, instead of using the non-diagonal matrix elements of each polarisation. This treatment is perfectly justified for weak anisotropy (less than 0.5), but

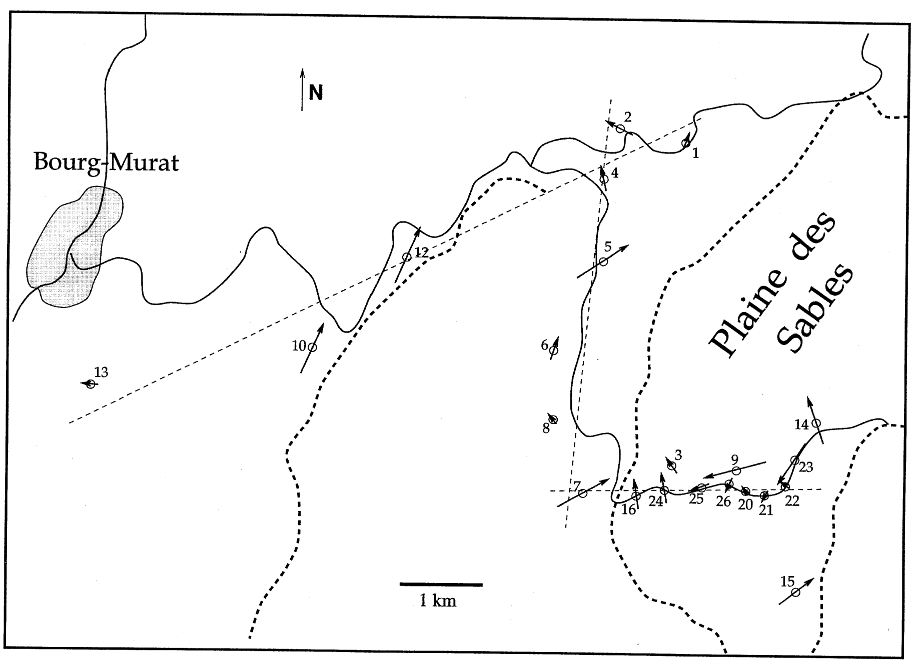

Fig. 4. Direction of the principal axes of the AMT tensor at all sites. Arrow lengths are proportional to the tensor anisotropy and reflect a departure from a 1D geometry. The dashed straight lines give the directions of the three sounding profiles.

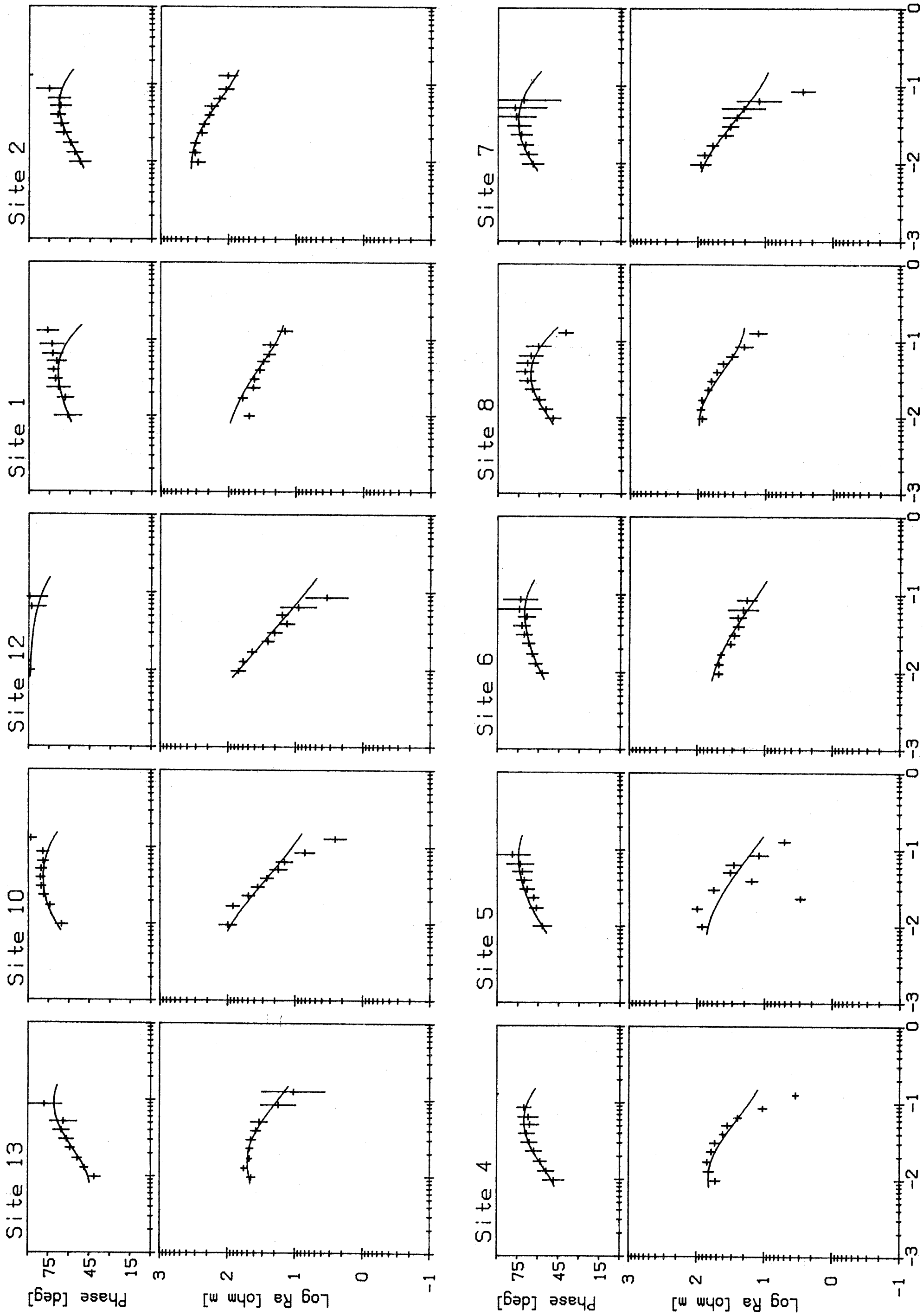

Fig. 5a. Model response (solid line) of the AMT apparent resistivity and phase at 10 sites outside Plaine des Sables. The crosses represent the main invariant of the MT response for the measured data.

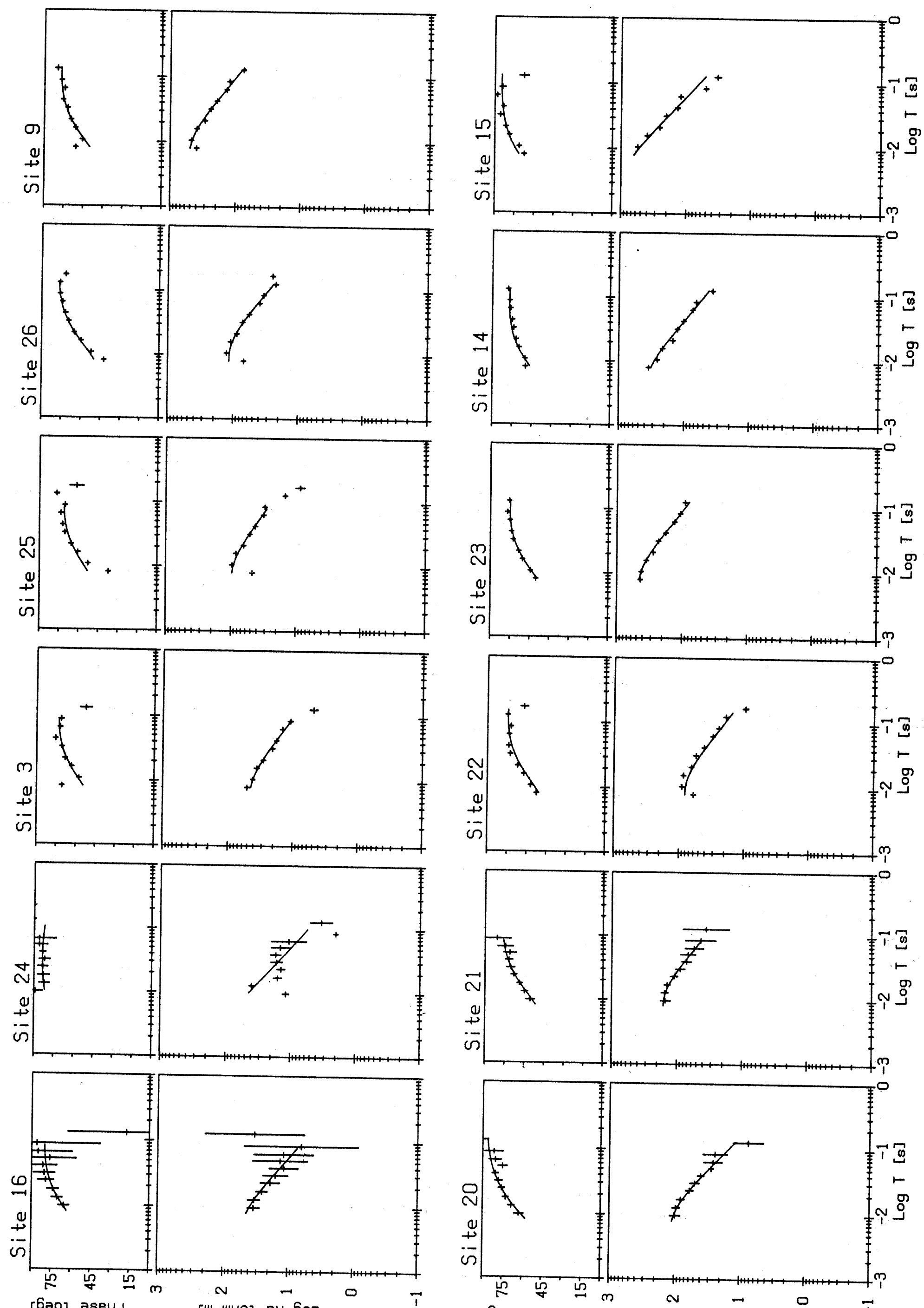

Fig. 5b. Model response (solid line) of the AMT apparent resistivity and phase at 12 sites inside Plaine des Sables. The crosses represent the main invariant of the MT response for the measured data.

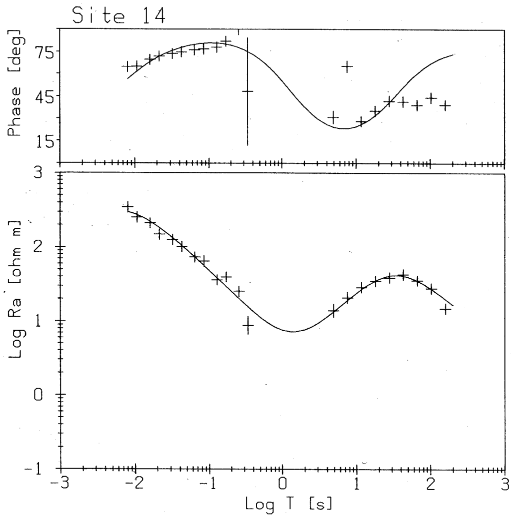

Fig. 6. Model response (solid line) of the broadband MT apparent resistivity and phase at site 14. The crosses represent the main invariant of the MT response for the measured data.

may lead to erroneous results for large ones. The very simple curves displayed by the apparent resistivity and phase suggest restricting the search for two-layer models at all sites. The resistivity decrease and phase increase indicate that a good conducting layer is overlaid by a more resistive one. Measured data and model responses are shown in figs. 5a,b. Figure 6, in turn, shows the same parameters at site 14, where long period data could be secured. This extended period range permitted the determination of the thickness of the conductive layer (layer 2), at least at this one site. It was found to be 195 m. The 1D models resulting from the modelling of the full dataset are shown on the profiles of figs. 7a,b. Note that fig. 7a shows a profile made up of 2 segments that originate at site 1 and point respectively NW and S (see profile locations on fig. 4). Because the AMT data of these profiles cannot furnish the thickness of the second layer, we have set it uniformly at the value found at site 14 (195 m). Tentative modelling of the bad-quality longer period data at other sites shows that this parameter is constant within a factor of 2 from site to site.

5. Geological interpretation

Looking at the AMT models of figs. 7a,b, and ignoring outlayers such as sites 2 and 23, we see that the vertical rock resistivity distribution is in accordance with that observed by Benderitter, with regard to the value limits (Benderitter, 1984, 1990) and Barthes *et al.* (1984). They all show the presence of a very good conductor overlaid by a more resistive cover. Whereas the cover has an average thickness of about 380 ± 150 m along the profile extending downhill on the W of Caldera II (fig. 7a), it appears that this resistive layer gets thicker when moving from W to E along the profile across Plaine des Sables (fig. 7b). Starting with 240 m at site 16, it reaches a thickness of almost 700 m at site 14. We interpret this good conductor as a clay horizon belonging to an ancient phase of the volcano (Phase 2) that was exposed at the surface prior to the filling of the caldera. Our modelling indicates that this layer slopes downhill toward the E with a dip angle of approx. 7°. As was pointed out with the magnetotelluric anisotropy in the previous chapter, care must be exercised not to overinterpret 1D models like those of figs. 7a,b. For instance, the thrust fault occurring between sites 3 and 25 (fig. 7b) may be part of the circular dip-slip fault system associated with the caldera, or just be a modelling artefact. In Plaine des Sables, moreover, the location of our sounding sites is confined within a narrow W-E path (at least between sites 16 and 22). Therefore, there is no available information about a possible N-S component of the dip. However, it is worth mentioning that site 3 and the easternmost sites (14, 15), which noticeably overstep the profile laterally, do not show any appreciable N-S component.

Some new geological facts are revealed by these AMT measurements when the results obtained on the 2 profiles are compared: It is clearly shown that the basement of Plaine des Sables caldera, unlike its surface, is not level, but slopes downhill towards the E with a dip angle of 7°. This observation underscores the fact that, in the particular climatic environment of Reunion Island, hydrothermalisation of basalt unfailingly occurred within the first

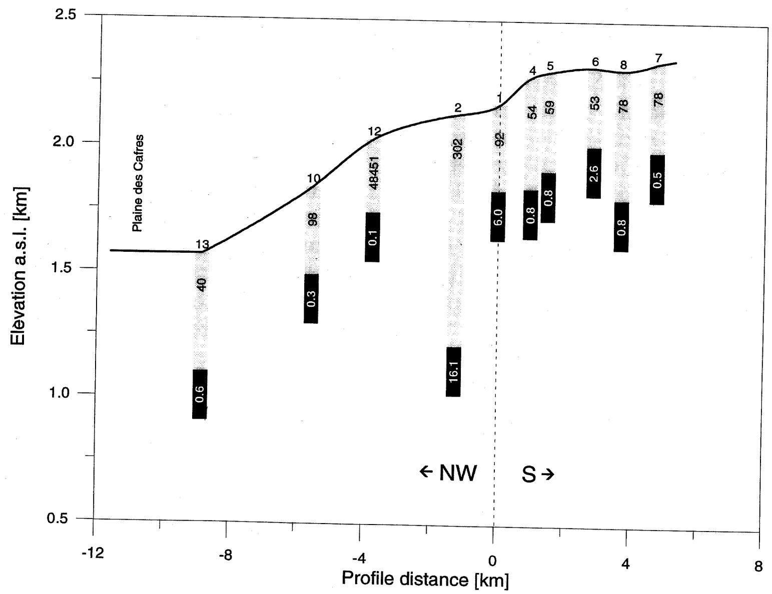

Fig. 7a. Assemblage of 1D models resulting from the modelling of the data set located outside Plaine des Sables. Note that this figure shows a profile made up of 2 segments that originate at site 1 and point respectively NW and S (see profile locations on fig. 4).

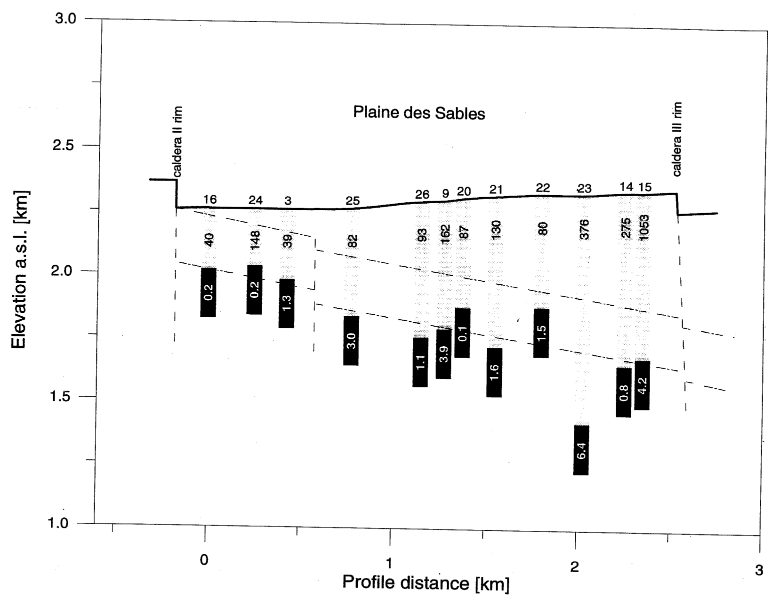

Fig. 7b. Assemblage of 1D models resulting from the modelling of the data set located inside Plaine des Sables (see profile locations on fig. 4). The lower dot-dashed line gives the roof of the modelled good conducting layer. The upper one gives the deducted topography of the Phase II sediments.

200-500 m depth, provided enough time was available to thoroughly carry it out. But AMT soundings in the Plaine des Sables show that the depth to the conducting layer can reach 700 m at the eastern end, close to Enclos Fouqué, the last caldera. Owing to the recent age of Caldera II fillings, which settled during Phase III, the hydrothermal alteration of the lava flow and of the pyroclastic lapilli that carpeted the ancient caldera is probably very limited, and the electrical resistivity of these shallow rocks therefore remains quite high. The observed dipping conductor must lie underneath, in much older sediments, probably those that settled during Phase II. We know, from data sampled along the western profile (fig. 7a) and from other authors (Barthes *et al.*, 1984; Benderitter, 1984, 1990) that for such old rocks the clay conductor is to be found at approx. 200 to 500 m depth. The excess thickness reported in Plaine des Sables can be accounted for by the recent fillings of Phase III, leading to propose the electrical conductivity model of Plaine des Sables shown in fig. 8. According to this model, the throw associated with the Plaine des Sables caldera collapse should not exceed 100 m, which is the current cliff height. Rocks belonging to Phase II are likely to be found at very shallow depths along the western border, W of site 16.

The observed basement slope direction (East) and steepness (7°) could be tentatively explained by two different actions:

1) The Caldera II collapse was induced by the depletion of the magma chamber, leaving behind a bowl-shaped topography. Under these circumstances the western side of the Plaine des Sables basement must slope down toward the volcano center. To our knowledge, however, such steep slopes have never been reported for shield calderas.

2) According to Duffield *et al.* (1980), catastrophic landslide episodes are scattered throughout the history of Piton de la Fournaise. They are responsible for the opening of the calderas toward the ocean. Such landslides have been regarded as a mixture of caldera collapses (vertical motion) and lateral displacements (Bachèlery and Mairine, 1990). The slope of the Plaine des Sables basement may therefore also be explained by this combination of terrain movements, its continuation toward the ocean, under the volcano, corresponding geometrically to the area known as Grand Brûlé (see figs. 1 and 8). We suppose that this gently sloping coast makes up the eastern part

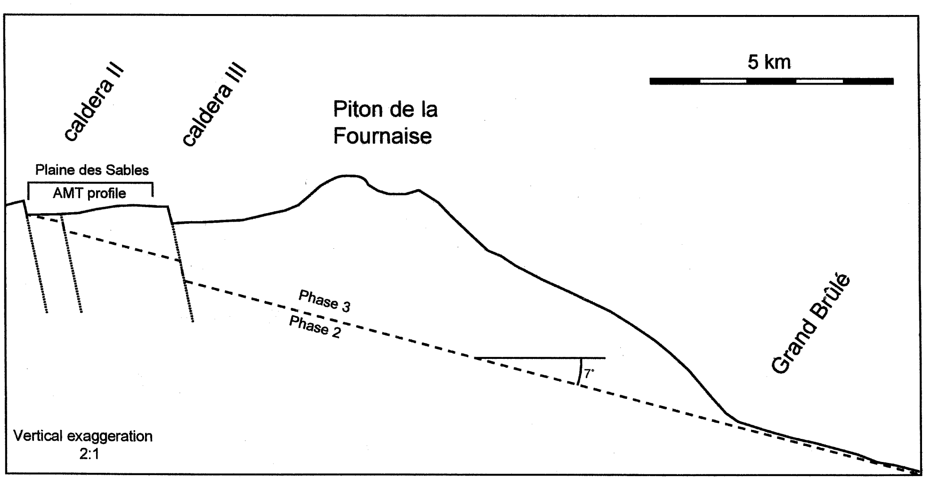

Fig. 8. Model of the geological structure of Plaine des Sables and beyond, as inferred from 1D modelling. The dashed dipping line shows the limit between Phases II and III.

of Caldera II. Unlike Plaine des Sables, no significant recent sediments from Phase III are present there. This is confirmed by the magnetotelluric soundings of Barthes *et al.* (1984), in which the depth to the conductive layer is found to range between 200 and 500 m, thus indicating an ancient origin of the rocks. In the present instance the fact that the continuation of Plaine des Sables toward the ocean can be observed on the coast (Bachèlery, 1981) confirms our model.

6. Conclusions

Audio magnetotelluric data have been collected on two profiles across the western part of Piton de la Fournaise. One-D modelling of these data has been carried out. Using the depth information of the ubiquitous hydrothermally-generated clayey layer, collected on older rocks by ourselves and other authors, and being aware of the recent age of the uppermost sediments, we have shown that the topography of the Plaine des Sables basement is somewhat unexpectedly *unrelated* to that of the surface, displaying a 7° dip toward the volcano summit. Moreover, the vertical throw associated with the caldera collapse has at most a height of about 100 m, similar to the height of Caldera II rim.

The coastal slopes of Grand Brûlé can be correlated geometrically across the volcano summit to the basement slope of Plaine des Sables. This assemblage makes up the entirety of the tilted Caldera II. We conclude that the past and present actions of successive landslides of the edifice has left large-scale imprints on the Piton de la Fournaise volcano.

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