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# A magnetotelluric study across Sete Cidades Volcano, São Miguel Island, Azores

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**Resumo**

Dados magnetotelúricos de amplo espectro de freqüência (8 a 30000s) foram coletados em 4 estações em um perfil de direção N20E cruzando o Vulcão das Sete Cidades, Ilha de São Miguel, Açores. O processamento dos dados consistiu na aplicação de método robusto para a determinação do tensor impedância e a decomposição deste em parâmetros locais e regionais. O *strike* geoelétrico encontrado, N60W, é paralelo aos grandes falhamentos regionais que afetam a área estudada. A interpretação de modelos inversos 1D aponta para a existência de uma zona hidrotermal situada abaixo de 1 km de profundidade.

Palavras-Chaves: Magnetotelúrica, Vulcão das Sete Cidades, Anomalias de condutividade, Reservatório hidrotermal

***Abstract***

*Along a N20E striking profile at Sete Cidades Volcano (São Miguel Island, Azores) we recorded broadband magnetotelluric data at 4 sites in the period range 8s – 30000s. Data were processed with a robust code and decomposed into local and regional Groom-Bayley parameters. The geoelectrical strike, N60W, is in agreement with one of the major fault zones in the area. 1D inverted models indicate the existence of a hydrothermal zone (probably a magma chamber) bellow 1 km depth.*

*Keywords: Magnetotelluric, Sete Cidades volcano, Conductive anomalies, Hydrothermal reservoir*

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## 1. Introduction

Electromagnetic measurements are widely used to probe the structure of the Earth's crust from depths of few meters to several tens of kilometers. Electrical conductivity of crustal rocks shows very little dependence on the resistivity of minerals but on the material in-between. Indeed, the physical property that is most affected by changes in water content, temperature, graphite or ore minerals within the rocks is the electrical conductivity.

The magnetotelluric investigation shown here is within the framework of a Brazilian-Portuguese research program to study the Azores triple junction. The goals in this project are twofold: (i) understand the crustal/mantle structure of the triple junction; (ii) detection of electrical anomalies which could be linked directly to volcanic activity in one of the three main volcanoes in São Miguel Island (i.e. hydrothermal fluids or the hot melt).

In this paper we present the results from a profile extracted from a MT/GDS broadband survey done at Sete Cidades Volcano, São Miguel Island. The referred profile, striking N20E, crosses the main crater. We give the interpretation of 1D inversions realized at the TE mode sounding curves and discuss the significance of the shallow conductivity anomaly found in the area.

## 2. Geological framework

The Azores archipelago is located within the framework of the triple junction between European, African and North-American plates (Figure 1). It is composed of 9 volcanic islands that emerge, between the latitudes 37$^o$–40$^o$N and the longitudes 25$^o$-31$^o$W, from the so-called Azores Plateau (Lourenço *et al.*, 1998). The Mid-Atlantic Ridge (MAR), the East Azores Fracture Zone (EAFZ) and the Terceira Rift are the main important fault system in this area, but the way how they interact is still not well understood (Queiroz, 1998). The present knowledge of the evolution of the Azores is mainly constrained by focal mechanism of earthquakes. They show essentially a combination of WNW-ESSE normal faulting, with a E-W right lateral strike slip fault system (McKenzie, 1972; Buforn *et al.* 1988).

Much of the research done previously has focused on the evolution of the triple junction, but comparatively little is know about the geology of São Miguel Island and the Sete Cidades Volcano. São Miguel, the principal island of Azores archipelago, can be subdivided into four main areas (Trota, 1998), three in the western characterized by active volcanics systems: Sete Cidades (Fig. 2), Fogo and Furnas; and the oldest part of the island, the Nordeste Volcanic Complex. Associated to the each volcanic system there is, at least, one geothermal reservoir (Forjaz *et al.*, 1993).

Sete Cidades is considered to be the most active central volcano known in the region (Queiroz and Gaspar, 1998). This volcano has approximately circular summit caldera with approximately 6000 km diameter. Pumice cones, maars and domes are observed within the caldera; while scoria cones and domes are the dominant structure outside. The regional tectonic regime influences the main fracture systems that can be identified in the volcano. The Mosteiro Graben, a pronounced NW-SE tectonic structure on the northwestern flank of the caldera, is interpreted to be a sub-aerial segment of the Terceira Rift (Queiroz and Gaspar, 1998). Several scoria cones within the caldera are cleared controlled by Mosteiro Graben. At the western part of the volcano, the E-W alignment of domes is considered to be a superficial expression of a deep oceanic fracture. Due to Queiroz and Gaspar (op.cit.), the intersection of the NW-SE and E-W trends probably determined the positioning of Sete Cidades genetic center.

## 3. Data acquisition and processing

A commercial single station long period MT system (LiMS 5.0) was used in this study to record the five components of the electromagnetic fields (Ex, Ey, Hx, Hy and Hz). The present dataset is composed of four stations in a profile crossing the main caldera of Sete Cidades

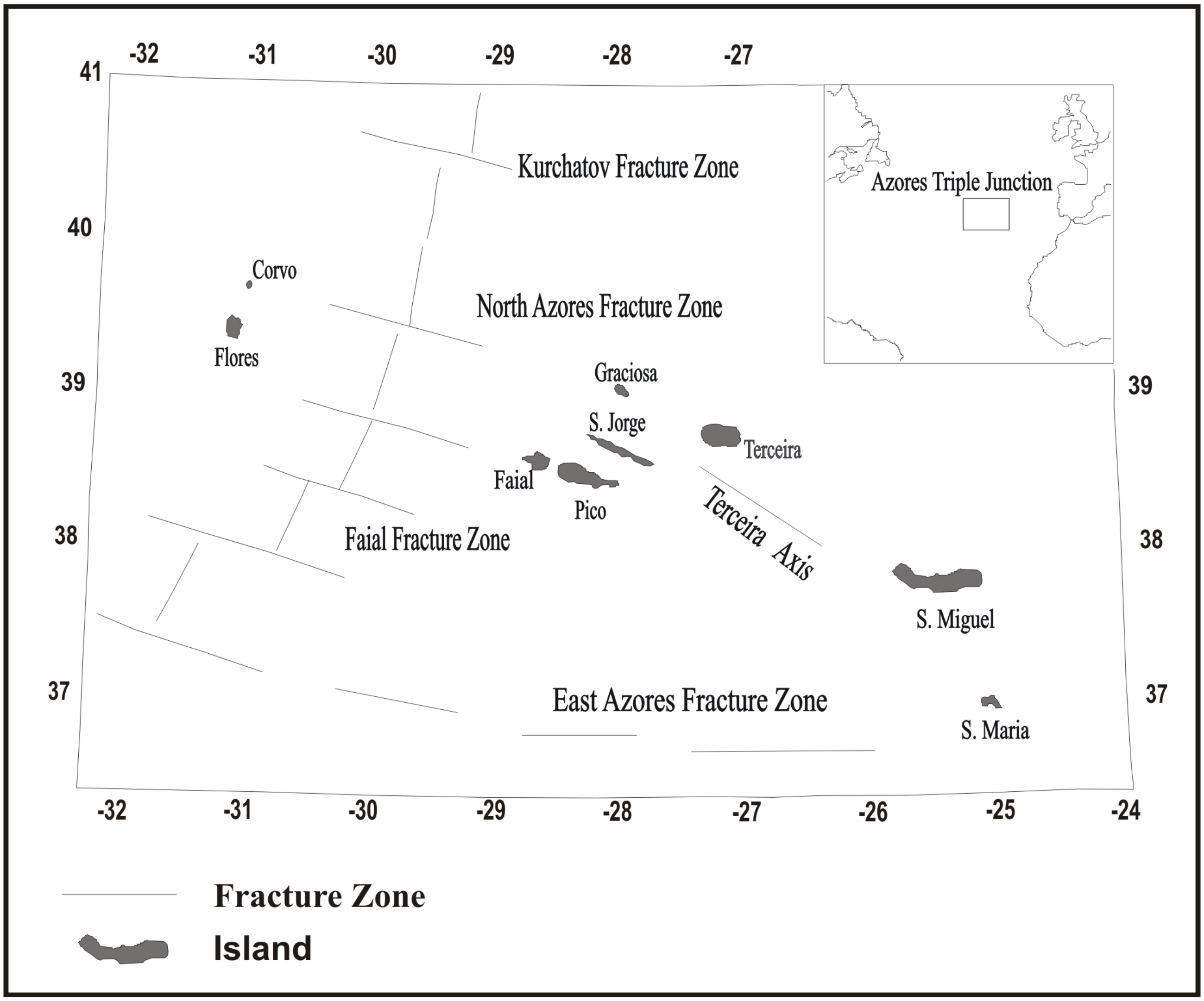


*Fig. 1. Azores triple junction area, several fracture zones are evidenced. The Azores archipelago is composed by nine islands.*

volcano. Figure 2 shows the site location, two stations are within the main caldera and the other two are outside it. The referred profile strikes N20E, which direction is approximately perpendicular to Mosteiro Graben fault system.

The telluric fields were recorded in cross-configuration with 100 m dipoles, while the magnetic date were measured with one induction coil that recorded simultaneously the horizontals and the vertical components. At all sites the measurements were aligned to the magnetic North. Due to our two main goals at the joint project we have employed two different strategies for data acquisition: Site 07, situated at a small secondary crater inside the main caldera (Fig. 2), was acquired with a sampling rate of 1 s and recording time of 7 days (Fig. 3a). Station 07 is located in the border of Mosteiro Graben. The other sites were recorded with a sampling rate of 4 Hz and recording time of at least 24 hours (Fig. 3b). This strategy allowed us to have a broadband dataset ranging from 8 to 30000 s.

The MT tensor elements and geomagnetic (GDS) transfer functions were estimated using the Jones-Joedick robust scheme (Jones and Jödicke, 1984). Most of recordings sites were disturbed by noise, specially the telluric fields. São Miguel Island is the most populated area of Azores archipelago, most part of the population lives in small villages within and around the crater, all of which have electricity. Prior to the robust estimation the time series were analyzed to cut off bad data segments, that generally occurred at both ends of the register (Fig. 3). Figure 4 shows apparent resistivity, phase curves and induction arrows for the station 04 as an example of data quality.

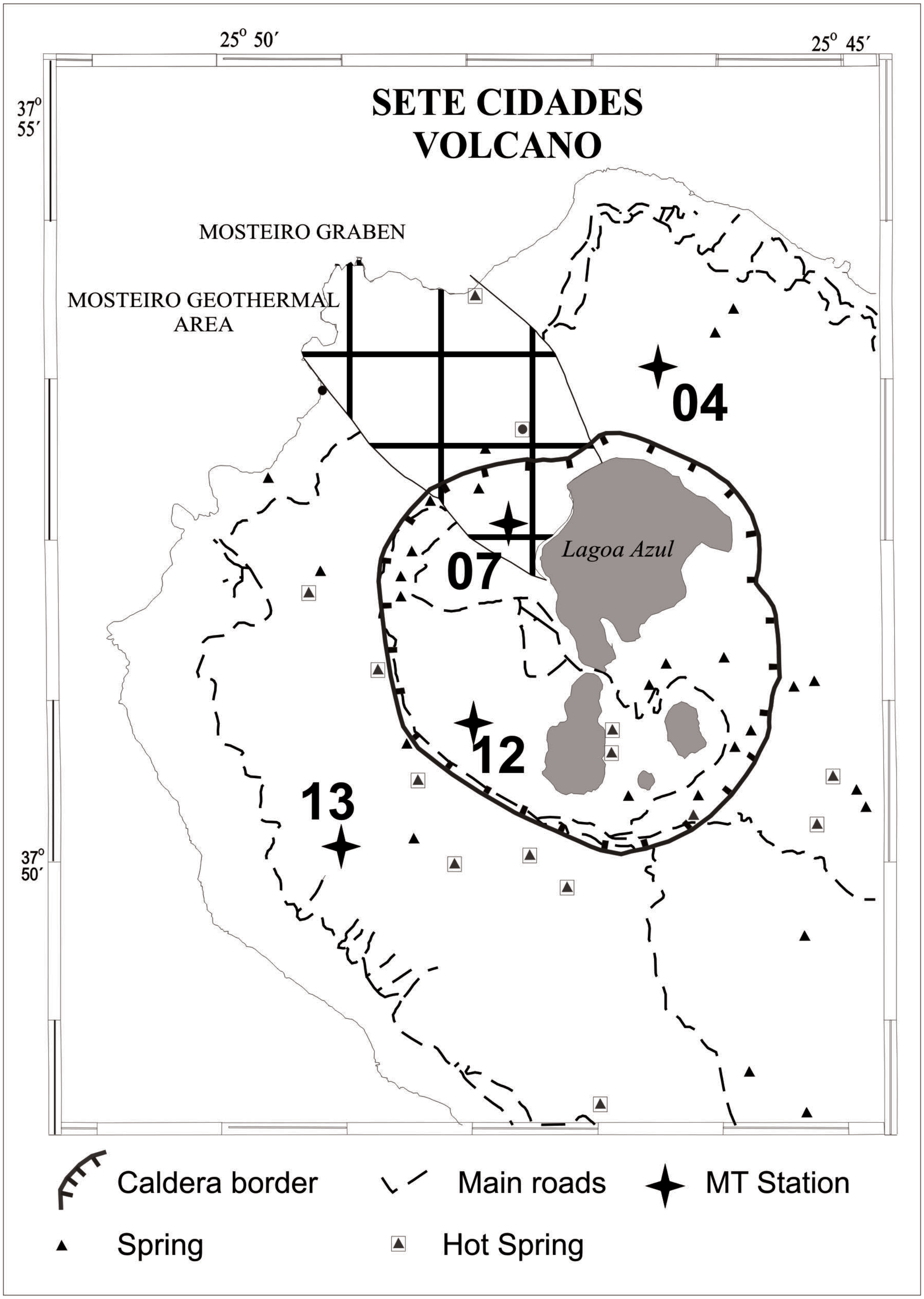


*Fig. 2. MT stations at Sete Cidades Volcano, São Miguel Island. Mosteiro Graben, a geothermal zone, is defined by the hashed area. The several known hot springs are plotted in the map. Modified from Forjaz et al. (1993).*

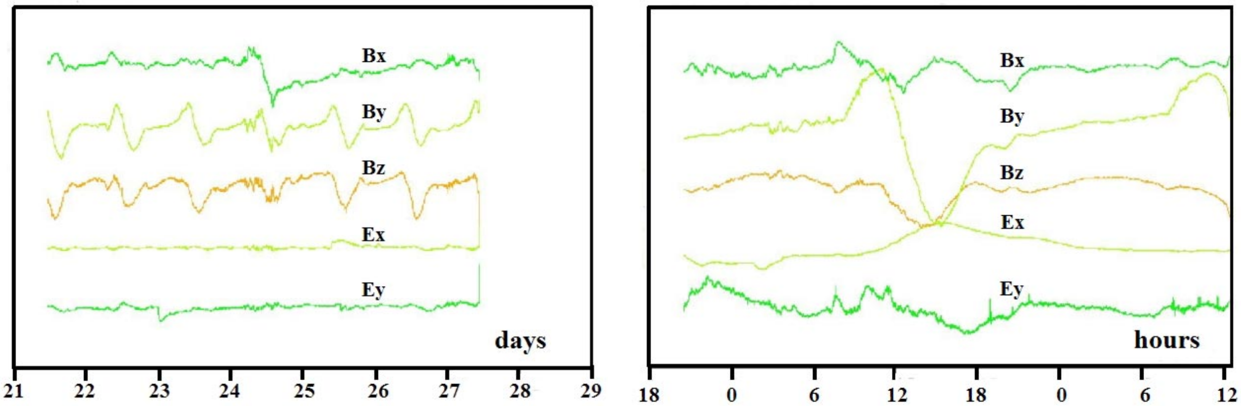


*Fig. 3. (a) Raw time series at site 07, with sampling rate of 1 s and recording time of 7 days, three magnetic ($B_i$) and two electrical ($E_i$) channels. (b) Raw time series at site 13, with sampling rate of 4 Hz and recording time of 40 hours, three magnetic ($B_i$) and two electrical ($E_i$) channels.*

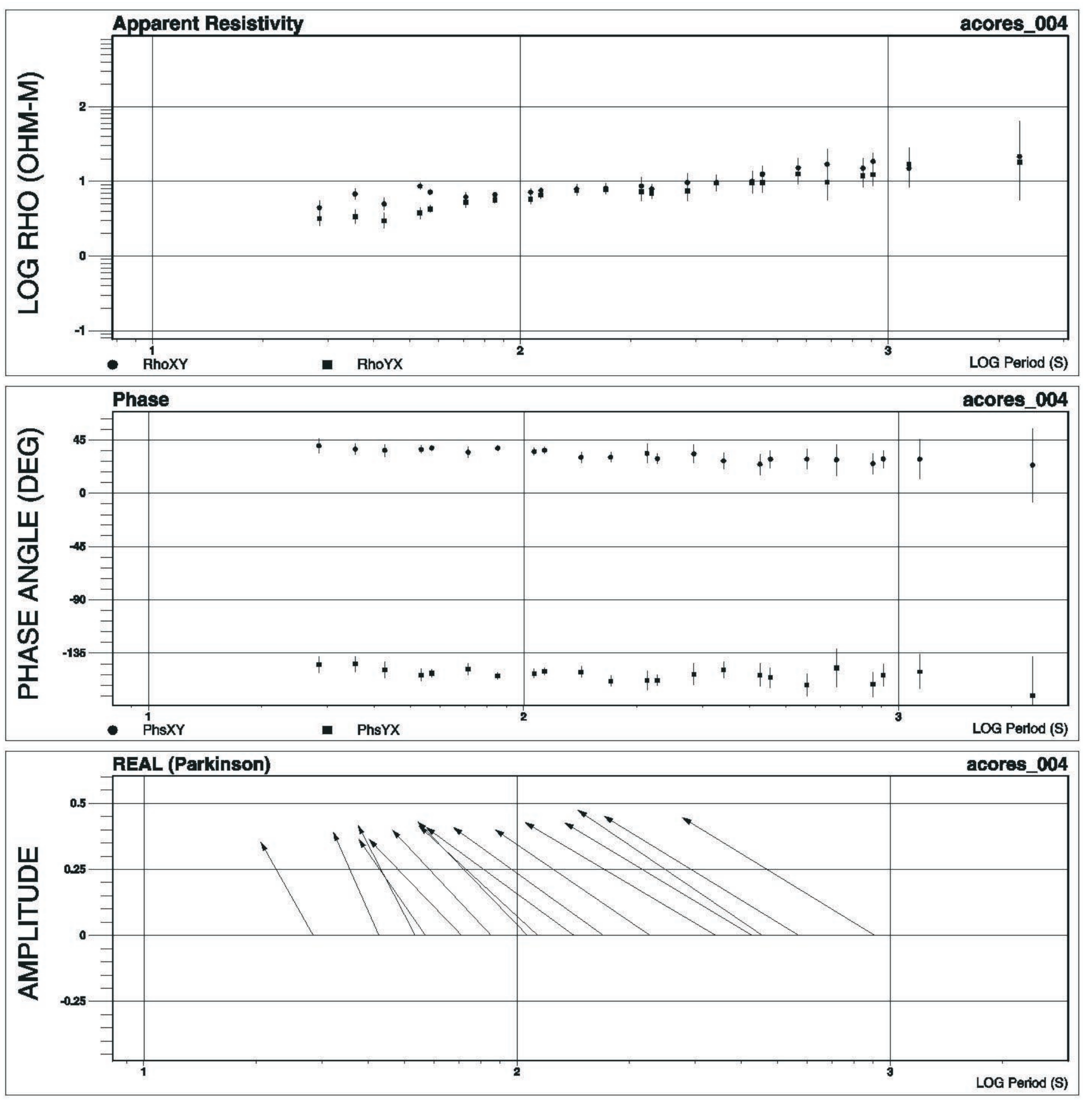


*Fig. 4. MT parameters for site 04. Upper panel – apparent resistivity for TE (XY) and TM (YX) modes. Central panel phase for TE (XY) and TM (YX) modes. Lower panel – real part of induction arrows using Parkison convention.*

## 4. Strike determination ans distortion analysis

The use of conventional Swift's method (Swift, 1967) has shown that the strike angle is fairly well determined for the whole frequency range at the four studied sites, with an average value of N35E. The tipper strike is also well determined with an average value of N30E. It is interesting to note that these values are nearly frequency-independent. This result is quite surprisingly as a volcano is essentially a 3D structure. Therefore, we should not expect to have a preferential strike arising from the dataset. The geoelectrical strikes found are orthogonal to the strike of Mosteiro Graben fault zone (N60W). Due to the inherent 90º ambiguity in strike estimation, that could be an indication that this 2D regional structure have a strong influence on our long period dataset.

To investigate further the data dimensionality and determine the regional strike, Groom-Bailey decomposition (Groom & Bailey, 1989) was applied to each site. This decomposition scheme assumes that the regional response is 2D and the electric field has been distorted by a local 3D structure. The analysis of the regional impedance and the local distortion parameters (twist and shear) was done at the whole period range. The authenticity of the proposed model was tested with a chi-square test (Chave & Thomson, 1989). The obtained regional geoelectric strike, N60W, was selected as the one producing the smallest frequency-independent misfit in relation to the distortion model. The twist and shear values were fixed to a constant values at which they displayed a near independent behavior. The fixed values of strike, twist and shear were employed to recover the regional impedances (Fig. 4).

Induction arrows are particularly useful to unveil lateral conductivity contrasts (Ritter *et al.*, 1998) and may be useful to constrain strike estimation. In the Parkinson convention (Hobbs, 1992), as plotted in Figure 4, the real vectors points towards the conductive body or a nearby conductivity contrast. In our case the real induction vectors are very large and point towards the coastline at all studied sites, indicating that the conductive ocean surrounding São Miguel Island has considerable effect on the MT/GDS data at the studied period range.

## 5. 1D inversions

A general first order 1D model for the four sites of Profile P1 was obtained from the inversion of the TE mode data. After the decomposition, the latest unknown parameters are the correct level of the apparent resistivity curves. The build up of electrical charges nearby small-scale inhomogeneities distort the amplitude of the electric fields. The magnetic fields and phases are not affected, that results in a period-independent multiplicative shift of the apparent resistivity values, the so-called static shift effect (Jiracek, 1990).

To minimize any possible static effect in our dataset we performed the Fischer inversion (Fischer *et al.*, 1981). This algorithm does not rely on a start model, rather, it makes use of direct site data for information regarding layering. The Fischer inversion "automatically" finds out static shift by constraining a model parameter. In our case we constrained the minimum (0.1 ohm.m) and maximum (2000 ohm.m) resistivity values to all sites.

Figure 5 shows the results for the 1D layered-earth inversion for site 07 that is inside the main caldera. A distinguish feature in the inverted model is the presence of two conductive layers at depth. The shallower level (less than 10 ohm.m) occurs at approximately 1.2 km depth; while the deeper one (10 –20 ohm.m) occurs bellow 10 km. It is important to note that site 07 present relatively low resistivity values, this was previously expected as this station is located over a known geothermal area. The misfit between the model response and the TE data is quite good for the short period range, while at longer periods it becomes worse. At periods higher than 100 s a particular behavior appears: a steep ascending branch of the phases. That could not be predicted by the 1D inversion procedure. Similar behavior was found in a MT dataset from a similar caldera at Canary Islands (Pous *et al.*, 2002). These authors associate it to a combination of the ocean effect and some sort of current channeling around Canary Island.

## 6. Discussions and conclusions

Each inverted model is a smooth representation of the regional structure below a particular site. They are like small windows open to the broader regional structure than can be used for a first interpretation. Assuming each site retains the main features bellow, it should be possible to produce a regional interpretation on the combined information of all inversions. Such procedure allowed us to infer any lateral continuity that may exist among the 1D inverted models. This produces the stitched 1D section shown in Fig. 6.

That section is limited to 10 km depth because our main interest in this study is to understand the volcano system. The whole section

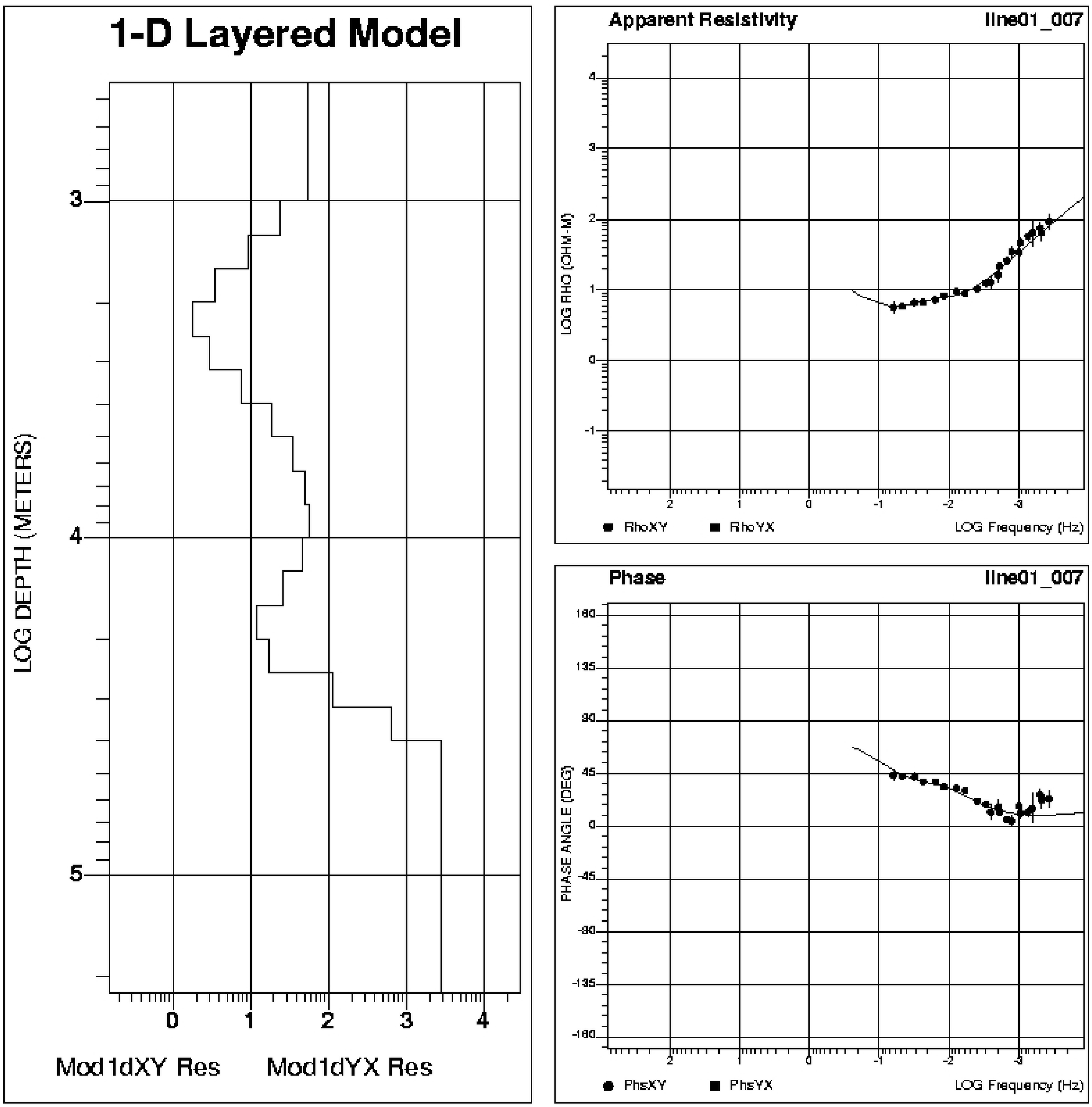


*Fig. 5. Layered 1D inversion at site 07. Left panel - 1D model; right panels – TE mode, comparison between data (filled circles) and model response (continuous line).*

is characterized by low to medium resistivity (1 – 200 ohm.m). A strong conductor beneath sites 12, 07 and 04, with depths ranging from 1.2 to 3.0 km indicate the existence of a hydrothermal reservoir at the central-northern portion of the main caldera. Our interpretation is in accordance with the surface geological knowledge, site 07 is located over a known geothermal zone (Fig. 2) bounded by Mosteiro Graben; and several hot springs are known in the studied area.

Our results are similar to a previous resistivity survey done at Água de Pau Massif (Andrade *et al.* 1995), encompassing the Ribeira Grande geothermal field, located about 30 km east of the present survey. In that field several well were drilled and two power plants (3.0 and 5.2 MW) were installed, generating part of the electric energy consumed by the islanders. The resistivity lows found within the scope of that survey were associated to hydrothermal circulation linked to the geothermal reservoir at 500 m depth. This interpretation was constrained by a priori geological and geothermal information given by the study of one drill hole (Muecke *et al.*, 1974).

At Sete Cidades volcano our results indicate that the hydrothermal reservoir is deeper than the encountered at Água de Pau volcano. A magma chamber beneath Sete Cidades volcano may be associated to the hydrothermal reservoir identified at 1.2 km depth. Further work with the interpretation of new sites collected around Sete Cidades main crater will allow the 3D modeling of the volcano (and the surrounding ocean).

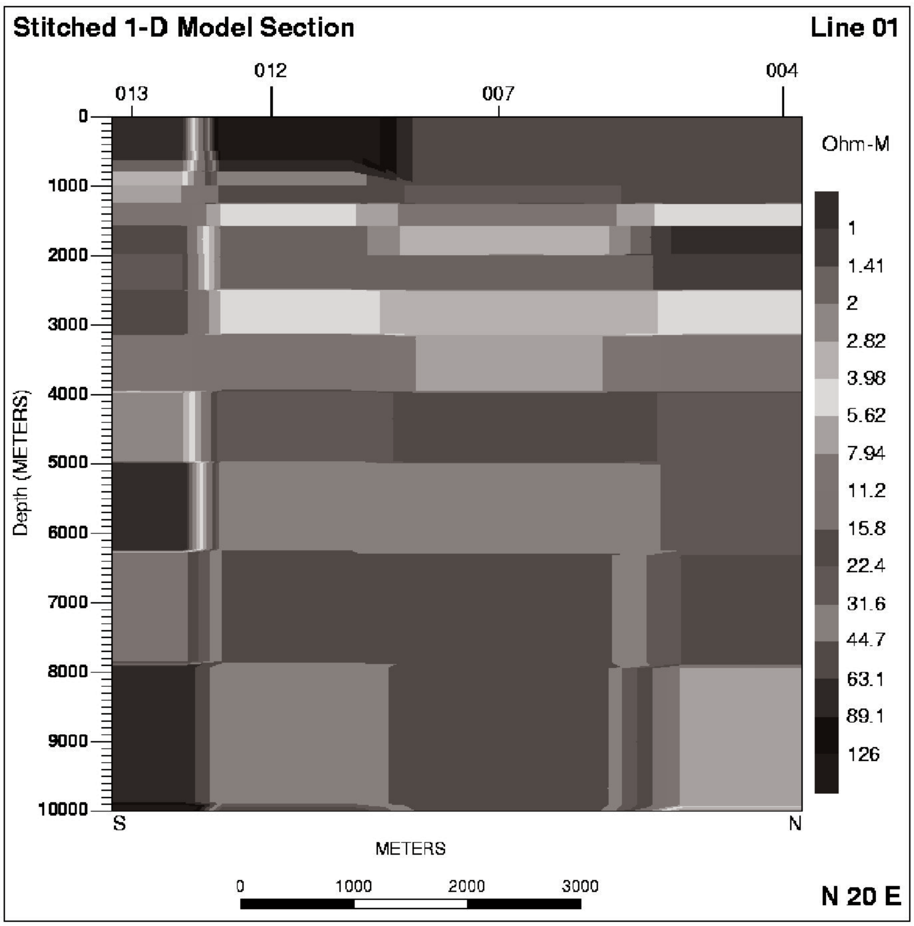


*Fig. 6. Stitched 1D section of the MT profile. Note that the lowest resistivity values are associated to site 07, bounded by Mosteiro Graben and a known geothermal zone.*

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