Electromagnetic Imaging of Sete Cidades Volcano, São Miguel, Azores.

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Abstract

In the present paper we analyze a broadband MT dataset recorded at Sete Cidades Volcano, São Miguel Island, Azores. Thirteen stations were recorded inside and outside of the main crater.

Robust processing and tensor decomposition analysis followed by 1D inversion were applied to the dataset in order to unveil Sete Cidades Volcano structure. A high conductive zone was found at depth within the main crater and in the western portion of the volcano.

Introduction

The Azores archipelago is located within the framework of the triple junction between European, African and North-American plates (Figure 1). The islands are associated with a region of positive gravity and residual depth anomaly which is interpreted as the surface expression of a mantle plume (McKenzie and O'Nions, 1995). The Mid-Atlantic Ridge (MAR), the East Azores Fracture Zone (EAFZ) and the Terceira Rift are the main important fault system in this area.

At the western end of the São Miguel Island is Sete Cidades Volcano, an approximately circular summit caldera with about 6000 km diameter, which has been built up from several phases of magmatic activity including the production of a lava shield and numerous explosive eruptions (Queiroz and Gaspar, 1998). The Sete Cidades volcano is one of the most active central volcanoes known in the region, at least 17 intra-caldera eruptions has been identified in the last 5000 years. In addition, there have been three offshore eruptions recorded in the last 400 years. Associated to this volcanic system there is, at least, one geothermal reservoir (Forjaz *et al.*, 1993).

The main fracture systems identified at the Sete Cidades volcano are strongly controlled by the major tectonic features. The Mosteiro Graben, a pronounced NW-SE tectonic structure on the northewestern flank of the caldera, is interpreted to be a sub-aerial segment of the Terceira Rift (Queiroz and Gaspar, 1998). 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.

The magnetotelluric investigation shown here is within the scope of a Brazilian-Portuguese research program to study the Sete Cidades Volcano and the crustal structure of the Azores Triple junction. One of the main goals of this project is the 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 discuss the results from a MT/GDS broadband survey done at Sete Cidades Volcano, São Miguel Island. We give the interpretation of 1D inversion applied to the MT sounding and discuss the significance of the shallow conductivity anomalies found in the area.

Data Acquisition and Processing

A commercial single station long period MT system (LIMS 5.0, Phoenix) was used in this study to record the five components of the electromagnetic fields (Ex, Ey, Hx, Hy and Hz).

The electric data was recorded with electrodes disposed in cross-configuration at 100 m dipoles. The magnetic data were recorded with one induction coil measuring simultaneously the two horizontals and the vertical components. At all sites the measurements were aligned to the magnetic North.

Data were recorded at two different sampling rates: Site 07, situated inside the main caldera with a sampling rate of 1 s and recording time of 7 days; and the other sites with a sampling rate of 4 Hz and recording time of at least 24 hours. That 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 robust code of Jones-Joedick (1984). Most of sites were disturbed by noise, specially the telluric fields. Prior to the robust estimation the time series were analyzed to cut off bad data segments.

To investigate the data dimensionality and determine the regional strike, the Groom-Bailey decomposition method (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 relates to the distortion model. Such direction is parallel to the Terceira rift, indicating that the electrical currents are strongly controlled by this tectonic feature.

The twist and shear values were then fixed to a constant value at which they displayed a near independent behavior. The fixed values of strike, twist and shear were employed to recover the regional impedances. In Figure 2 we show the apparent resistivity and phase curves for two MT sites.

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), the real vectors point towards a nearby conductivity contrast, as shown in Figure 3. In our case the real induction vectors are very large and point mainly toward the Terceira rift at all studied sites. This indicates that this regional feature surrounding São Miguel Island has considerable effect on the GDS data at the studied period range.

1D inversion

A general first order 1D model for all MT sites 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 4 shows the results for the 1D layered-earth inversion for site 07. 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.

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 sections shown in Figures 5-7 (profiles P1-P3). The sections are limited to 10 km depth because our main interest in this study is to understand the volcano system. All sections are characterized by low to medium resistivity (1 –200 ohm.m).

In the present paper we provide a detailed analysis of profile P1 (Figure 5). In this profile, a strong conductor beneath sites 12, 07 and 04 (depths 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 bounded by Mosteiro Graben; and several hot springs are known in the studied area. Site 3 in profile P2 (Figure 6) also shows a shallow conductivity anomaly.

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). Our results indicate that the Sete Cidades hydrothermal reservoir is deeper than 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.

The 1D models herein interpreted will be used as an initial guess in the 3D modeling/inversion exercise of the volcano (and the surrounding ocean).

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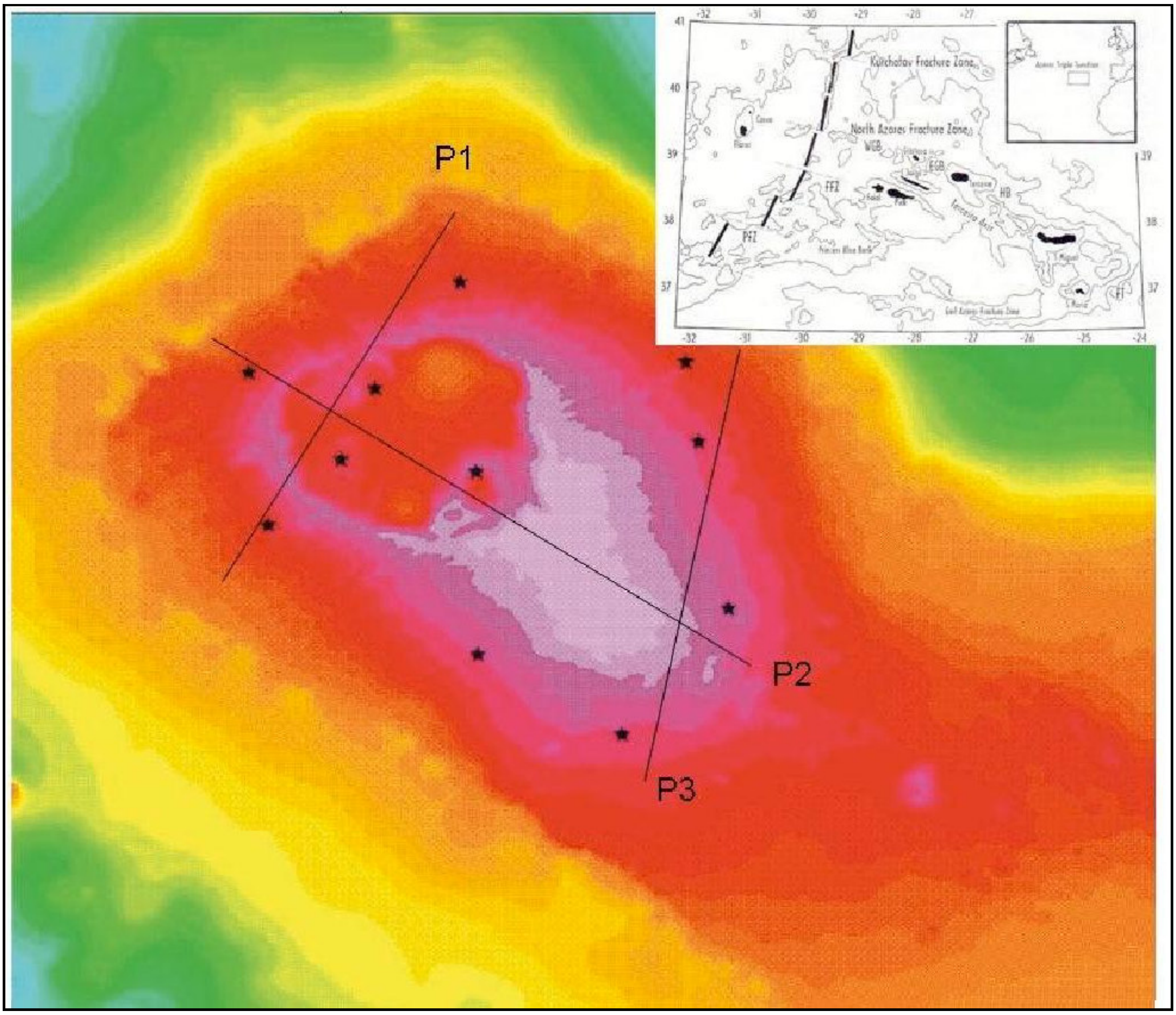

Figure 1- Sete Cidades Volcano and MT site location (black stars). P1, P2 and P3 are selected profiles shown in Figures 4, 5 and 6, respectively. Inset – Azores Triple junction location.

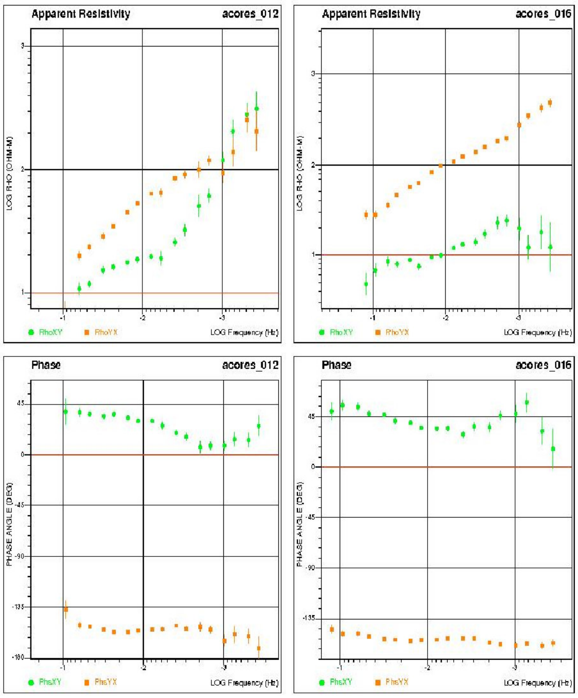

Figure 2 – Apparent resistivity and phase curves of sites 012 and 016. Orange curve – TM mode, green curve – TE mode.

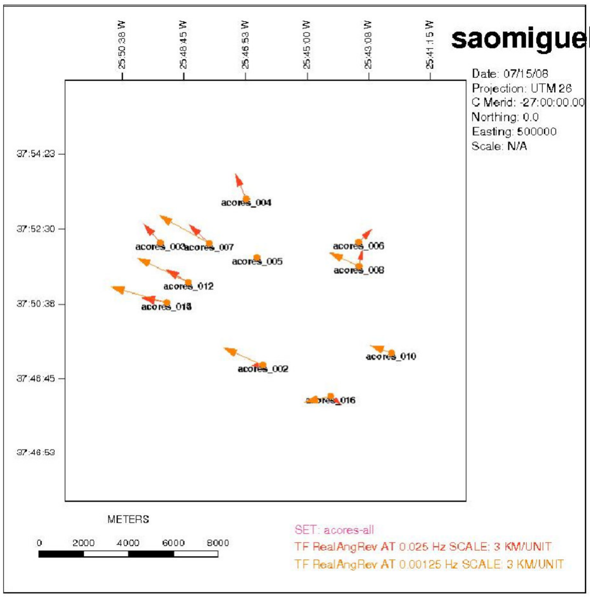

Figure 3 – Induction arrows at two different frequencies (0.025 and 0.00125 Hz), plotted in the Parkinson convention, arrows point towards the conductor.

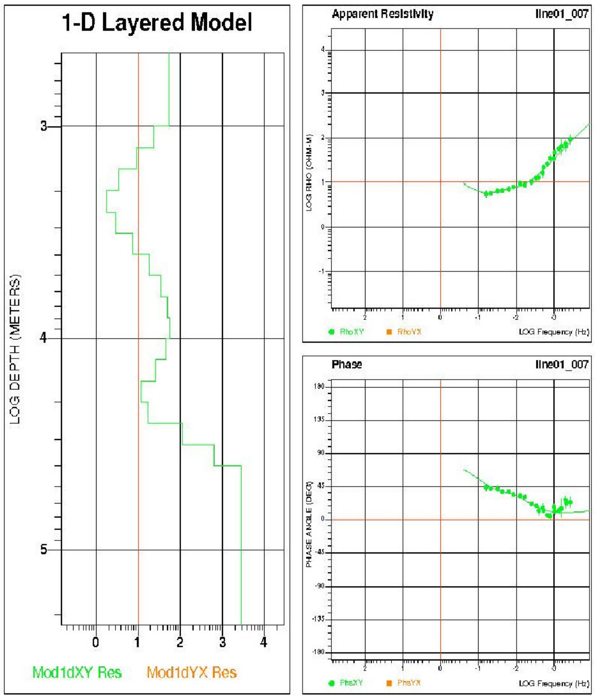

Figure 4 – Layered 1D inversion at site 07. Left panel - 1D model; right panels – TE mode, comparison between data (filled circles) and model response (continuous line).

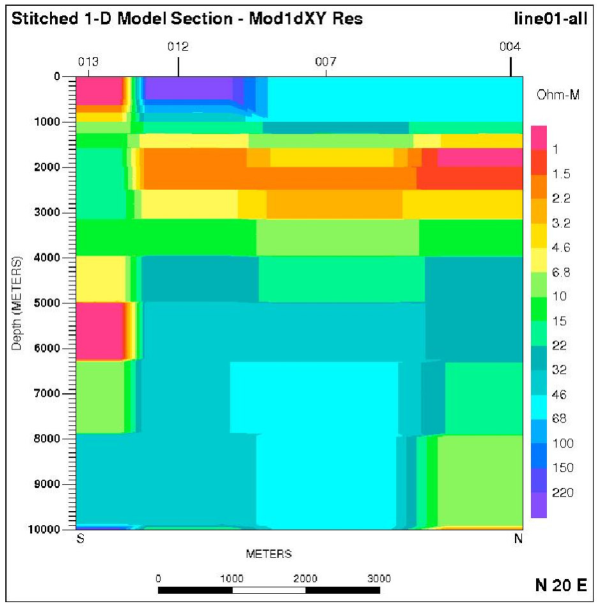

Figure 5 – Stitched 1D section of the MT profile P1. Note that the shallow resistivity values associated to sites 07, 12 and 04, bounded by Mosteiro Graben and a known geothermal zone.

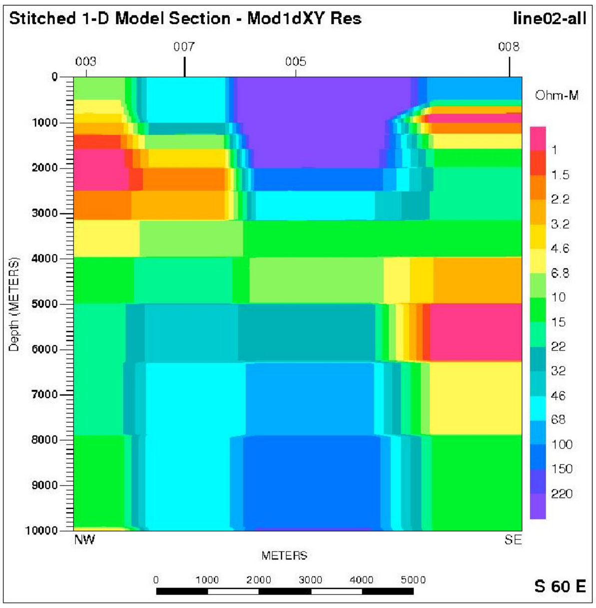

Figure 6 - Stitched 1D section of the MT profile P2. Note that the shallow resistivity values associated to site 07 and 03, at a known geothermal zone.

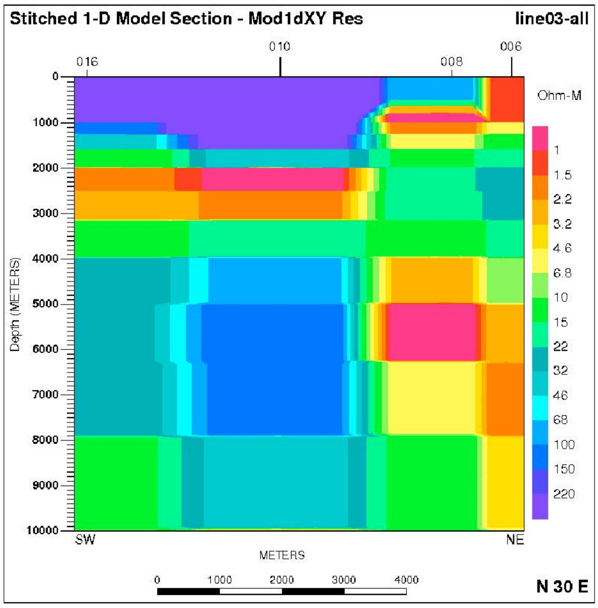

Figure 7 - Stitched 1D section of the MT profile P3. Note that shallow resistivity values are associated to all sites.