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THE APPLICATION OF AUDIO-MAGNETOTELLURIC SURVEYS ON SÃO MIGUEL ISLAND, AZORES PORTUGAL

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Abstract

Geothermal exploration and development has been under way on São Miguel island, Azores since 1975. This work had been restricted to the Fogo volcano, one of three dormant silicic volcanic centers on the island, with most of the work centered in a 10 km^2 area at low elevation on the north slope.

The USGS in 1982 and 1983 conducted reconnaissance natural-source audio-magnetotelluric (AMT) surveys of all three silicic centers to evaluate the potential for geothermal systems at each and to demonstrate the utility of the method in areas of difficult terrain. Results on Fogo showed a low resistivity trend extending from the present production area upslope to the caldera boundary. We infer that the upper part of this trend is the upwelling zone of a thermal plume which supplies the production area. Further exploration and drilling are now planned for this area. Other promising regions were defined on the south slope of Fogo and on the other two volcanoes.

Introduction

The Laboratorio de Geociencias e Tecnologia (LGT) of the Azorean Regional Government has been engaged in a program of exploration for, and development of, their geothermal resources since 1975. The exploration and development has concentrated on 4 of the 9 islands in the archipelago. The principal development has occurred on São Miguel island, which contains about 50% of the islands' population, near the town of Ribeira Grande. Several production wells have been completed, and in 1980 a 3 Mw generator was installed (Meidav, 1981). Well PV-1 provides the present steam production which appears to be from an outflow zone of a thermal plume centered higher on the Fogo (or Agua de Pau) volcano, and is insufficient to operate the generator at capacity. The maximum temperature observed in PV-1 was 226°C at a depth of 550 m measured from the wellhead. The LGT currently plans further exploration, drilling, and construction with the hope of producing enough steam for existing power plants and a propsoed 10 Mw power plant.

To assist the LGT effort the USGS carried out limited geological, geochemical, and geophysical investigations on São Miguel (Moore, 1983; Hoover and others, 1983) with funding from the Agency for International Development, USGS, and LGT. The USGS studies focused on the three major late quaternary silicic volcanic centers of São Miguel: Sete Cidades, Fogo, and Furnas (figure 1). All three centers have well developed calderas and each has erupted explosively numerous times during the past 5000 years (Booth and others, 1978). Following settlement of the island in the fifteenth century, each has erupted at least once.

On São Miguel, the majority of thermal manifestations occur within the caldera of Furnas, which has become a major tourist attraction. Although geothermal development in the Furnas area is not anticipated, due to the potential for damage to the hot springs and fumaroles, our studies there provided a reference for comparison with studies of the Sete Cidades and Fogo centers. On Fogo, the most prominent thermal features are fumaroles at Caldeiras Ribeira Grande, and Caldeira Velha (figure 1). Hot springs, generally aligned on northwest trends through these fumaroles, are also found at lower elevations on the north, south and east slopes. Caldeira Velha, at about a 400 m elevation, is the highest thermal manifestation. At Sete Cidades the only known thermal features are small hot springs on the coast at Mosteiros and Ponta da Ferraria (figure 1).

The purpose of the audio-magnetotelluric (AMT) work described below was to provide the LGT with reconnaissance electrical surveys on all three volcanic centers to help assess the potential of each for geothermal power, and to identify the more favorable sites at each center. Much of the prior electrical work on Fogo volcano was restricted to an area of about 10 km^2 (the shaded area in figure 4) in the vicinity of production well PV-1. In part, this was because of limitiations imposed by thick vegetation and very rugged topography above 200 m elevations. We hoped to demonstrate the advantages of natural-source AMT surveys in such an environment by providing better definition of the geothermal system presently being exploited.

Prior electrical work has been conducted only on Fogo volcano and will be discussed in conjunction with the AMT results obtained on Fogo.

AMT Surveys

The USGS scalar AMT system used in this survey has been described by Hoover and Long (1976), and Hoover and others (1978). Natural electromagnetic signals (sferics), generated by lightning storms are used to measure earth resistivity as a function of frequency from which resistivity as a function of depth may be determined (Cagniard, 1953). At each site two telluric dipole soundings are normally made at orthogonal orientations. For the Azores work northwest and northeast dipole orientations were used so that dipoles would be parallel and normal to the principal structural trend (northwest). For appropriate sites the two soundings would then give the principal values of the resistivity tensor. At a few locations only one sounding was obtained, because it was impractical to lay out a 25 m orthogonal electric dipole. Fifty Hz power is used on São Miguel, so power line notch filters in our equipment were modified accordingly.

Because low amplitude natural signals are used, noise sources are always a concern. The principal artificial noise sources are power lines and portable electric fences which are ubiquitous on the island. To minimize the noise, stations were located at least 200 m from electric fences or power lines and in some cases electric fences were simply disconnected. Noise due to ground motion from passing vehicles was particularly noticable, but posed no real problem because of its transient nature. For comparison purposes, one AMT site was located where Geonómics hád ṁade two modified Schlumberger soundings (VES) which were expanded orthogonally. Each of these were extended by an equatorial array to 4000 m AB/2. There was excellent agreement between the AMT and VES results. A complete tabulation of all AMT soundings is given by Hoover and others (1983).

AMT Results from Furnas and Sete Cidades

AMT resistivity mapping in the Furnas area identified an east-west trending, low-resistivity zone through the center of the caldera. This zone correlates with the known fumaroles and hot springs. Mapped faults within the caldera also trend east-west suggesting that faulting controls the localization of the surface thermal fractures. In this zone, apparent resistivities were generally below 10 ohm-m at 7.5 Hz. Similar low resistivities were observed to the south and east of the caldera near the coast. Sea water intrusion cannot be ruled out as the cause of the low resistivities observed near the coast because depths to the conductive layer are at or below sea level. However, the presence of hot springs in the nearby village of of Ribeira Quente (figure 1) suggests the possibility of a geothermal system probably localized on northwest trending radial faults.

An aeromagnetic survey of São Miguel, flown by Instituto Nacional de Meteorologia e Geoficica shows prominent magnetic lows within both the

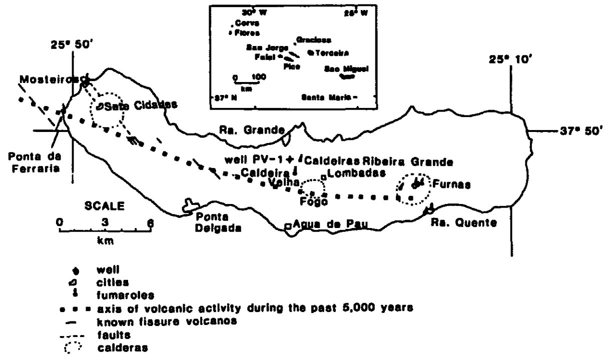

FIGURE 1
LOCATION MAP OF SÃO MIGUEL ISLAND, AZORES, ADAPTED FROM BOOTH AND OTHERS (1983) SHOWING PRINCIPAL TECTONIC FEATURES, FUMORALES, AND CALDERAS OF THE THREE DORMANT SILICIC VOLCANIC CENTERS ON THE ISLAND.

Furnas and Sete Cidades calderas. In both cases the magnetic lows are associated with low resistivity areas, implying destruction of magnetite and/or a shallow curie isotherm. No corresponding magnetic low is seen on Fogo.

On Sete Cidades, AMT resistivity mapping identified a prominent low-resistivity zone associated with a northwest-trending graben extending from the caldera rim to Mosteiros (Figure 2).

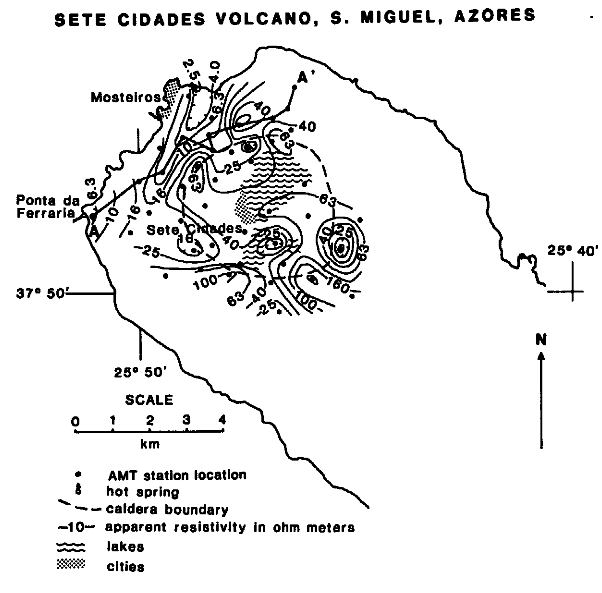

FIGURE 2
AUDIO-MAGNETOTELLURIC APPARENT RESISTIVITY MAP OF SETE CIDADES VOLCANO AT A FREQUENCY OF 7.5 Hz FOR A NORTHEAST ORIENTATION OF THE TELLURIC DIPOLE. RESISTIVITY CONTOURS ARE LOGARITHMICALLY SPACED, FIVE PER DECADE.

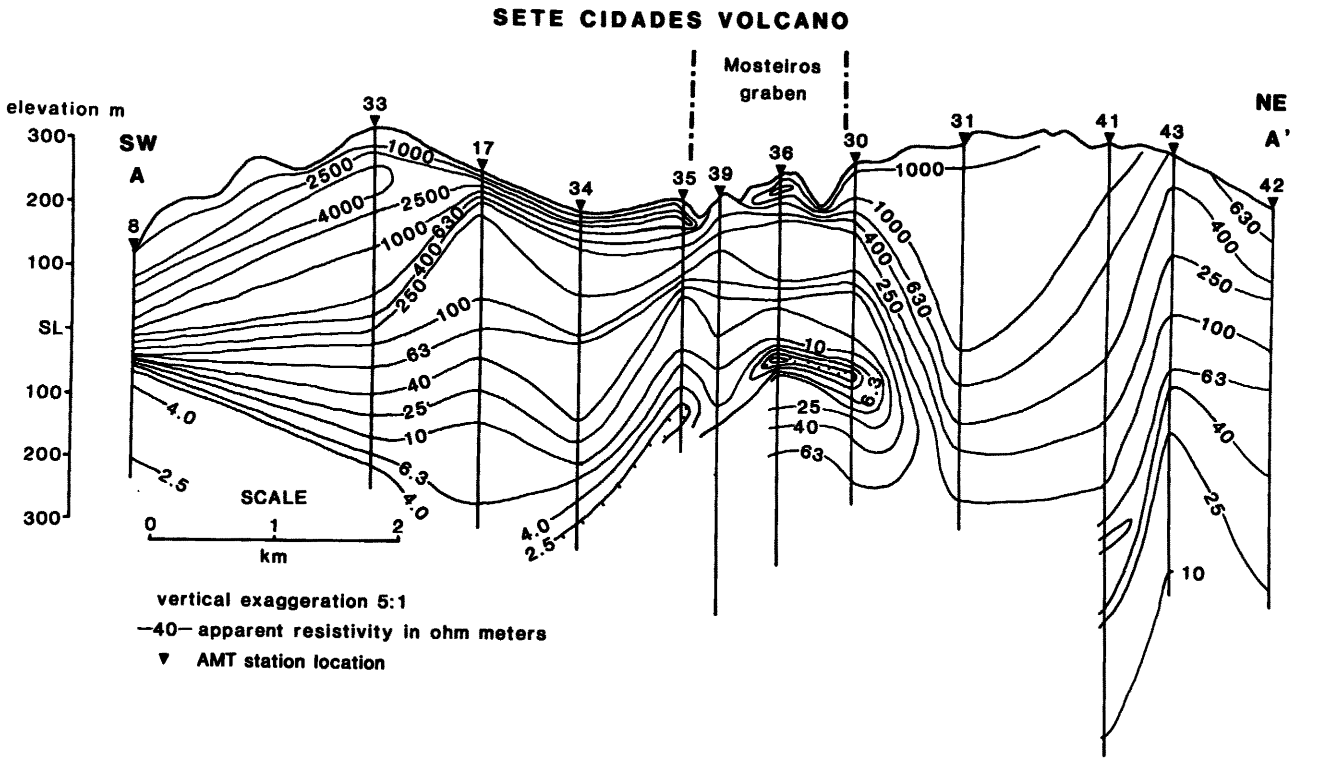

FIGURE 3
RESISTIVITY CROSS-SECTION ON THE NORTHWEST FLANK OF SETE CIDADES VOLCANO BASED ON ONE-DIMENSIONAL INVERSION OF AMT SOUNDINGS. NOTE THE LOW RESISTIVITY ZONE AT SEA LEVEL WITHIN THE MOSTEIROS GRABEN.

However, resistivities are generally higher inside the caldera than outside on the order of 100 ohm-m at 7.5 Hz. A similar picture was also seen at Fogo (figures 4 and 5). The higher resistivities within the caldera imply that porosities are lower than on the flanks, suggesting that collapse breccia within the caldera has been welded to form a relatively tight plug. If this is the case, then hydrothermal plumes may be restricted to caldera rim fractures and other fractures on the flanks. We do not mean to imply that a low-resistivity body is not present beneath the caldera surface. On the contrary, most soundings on São Miguel show decreasing resistivity with increasing depth to the maximum depth of exploration. The lowest frequency used, 4.5 Hz and thus the deepest looking, was not adequate to resolve the resistivity or thickness of the deep conductive layer.

In order to provide a better picture of the geoelectric section across the Mosteiros graben, a resistivity section (designated A-A′ in figure 3), was made. The cross section was compiled from one-dimensional inversions of scalar AMT soundings; the inversions were made using an algorithm of Bostick (1977). At each site, the logarithmic average of apparent resistivities from the two sounding orientations was used for the inversion, constrained so as not to rise or fall more rapidly with frequency than is possible for a one-dimensional earth. In laterally heterogeneous regions such as on São Miguel, sections based on one-dimensional inversions give only an approximate model of earth structure. The section (figure 3) clearly shows a low resistivity zone within the graben at about sea level, below which resistivities appear to increase. We interpret the low resistivity region as an outflow zone of thermal water, which probably originates near the caldera rim. Southwest of the graben, resistivities are less than 10 ohm-m at depths in excess of 500 m. Similarities with the producing area on Fogo suggest that much of the western flank of Sete Cidades may have geothermal potential. Because we believe that the hydrothermal systems are fracture controlled, the potential for a commercial geothermal system would be greatest in the Mosteiros graben near the caldera rim.

Earlier electrical studies of Fogo

Various unpublished electrical surveys have been made on Fogo volcano. The most complete and extensive work was that of Geonomics in 1976 (Meidav 1979, Meidav, 1981). Geonomics made 13 Schlumberger or modified Schlumberger soundings (VESes), 8 dipole-dipole lines, and a complete roving dipole survey of Fogo. This work identified a 10 km^2 low resistivity region (figure 4) in which all subsequent work was localized. Following the Geonomics work, the Insituto Nacional de Meteorologia e Geofisica (INMG) Lisbon, made 3 VESes and 4 short dipole-dipole lines, all near production well PV-1. A Portuguese contractor, Acavaco, made 4 additional

VESes in the area, and in 1983 an Italian firm, Aquater, made 23 more VESes. During 1979 General Electro-Magnetic Prospecting Inc. (GEMP) made 121 M.T.-5-E.X. electromagnetic soundings that covered about 20 km^2. This work extended up the north slope of Fogo to the vicinity of Caldeira Velha.

Meidav (1981) shows a composite interpretation map for the Fogo area, prepared by Geonomics. The boot-shaped, low-resistivity region which has been the focus of activity is shown by stippling (figure 4). Meidav interpreted the northwest trend along the sole of the boot to be a lateral discontinuity or fault. Subsequent VES data within this region has verified the low resistivities observed by Geonomics and has defined two northwest-trending zones of low-resistivity. These zones, in which apparent resistivities are less than 3 ohm-m for a VES AB/2 spacing of 1500 m, are also shown in figure 4. The westernmost trend, which we call the Caldeira Velha-Pico Vermelho trend, falls on a known fault zone from which steam is taken for current geothermal production. The easternmost low-resistivity trend, the Caldeiras trend, coincides with the fumaroles at Caldeiras Ribeira Grande, and is also believed to be related to faults. The VES data show steep resistivity gradients that are caused by the lateral discontinuity along the sole of the boot-shaped area identified by Geonomics.

Resistivity data from the M.T.-5-E.X. survey were presented as an isoconductivity map that identified 8 local areas of increased conductance. These data are difficult to evaluate, and show no clear relationship to known structures, to the other electrical data or data from the production wells.

<u>AMT Results on Fogo</u>

Because the production wells on Fogo appear to be located in an outflow zone, USGS recommended that LGT pursue exploration at higher elevations on the volcano, in hopes of defining a region where the geothermal system is upwelling (W. E. Duffield personal communication). LGT, however, was unable to obtain VES measurements higher up the north slope. The goal of the AMT survey on Fogo was to obtain equivalent data in areas where topography and vegetation make conventional VES methods impractical.

Figure 4 shows an AMT apparent-resistivity map prepared from our data. Fifty stations were obtained; about half of the stations were concentrated on the north slope, in the area of primary interest. The data show a southeast-trending zone of resistivity lower than 10 ohm-m which extends from the production well PV-1 along the Pico Vermelho-Caldeira Velha trend to within 2 km of Lagoa de Fogo. The lowest apparent resistivities are in the vicinity of Caldeira Velha; this pattern correlates well with the resistivity pattern of the VES data.

The Caldeiras trend that was identified in the VES data also appears in the AMT results although not as prominently. The AMT results indicate that the Caldeiras trend probably extends to Lombadas,

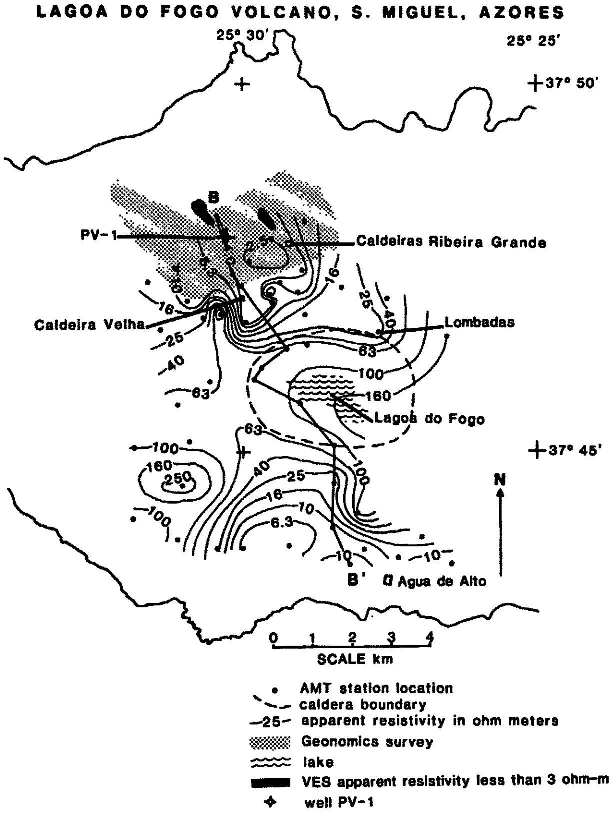

FIGURE 4
AUDIO-MAGNETOTELLURIC APPARENT RESISTIVITY MAP OF FOGO VOLCANO AT A FREQUENCY OF 7.5 Hz FOR A NORTHEAST ORIENTATION OF THE TELLURIC DIPOLE. STIPPLING SHOWS A LOW RESISTIVITY AREA IDENTIFIED BY GEONOMICS (MEIDAV, 1981) AND SOLID BLACK AREAS ARE REGIONS UNDER 3 OHM-METERS AS DEFINED BY VES WORK.

where carbonated mineral water is bottled for local consumption. We infer that the southeastern ends of these two low-resistivity trends approximately coincide with the region where hot water is upwelling. The trend terminations are close to an inferred old caldera rim, which probably acts as a control for upwelling water that rises along the caldera ring fractures and then flows out along northwest-trending normal faults.

Within the Fogo caldera, and on the western flanks of the mountain, resistivities are high. Low resistivities are observed on the south side of the mountain. Although the station density in that area is insufficient to adequately define trends, the low resistivities may be related to the pervasive northwest structural alignment on São Miguel; the low resistivities fall approximately on the Pico Vermelho-Caldeira Velha trend.

A geoelectric section across Fogo, designated B-B′ (figure 5) was constructed in the same way as for Sete Cidades. The section runs along the Pico Vermelho-Caldeira Velha trend and includes the important low-resistivity regions on both sides of the volcano. The resistive central plug, similar

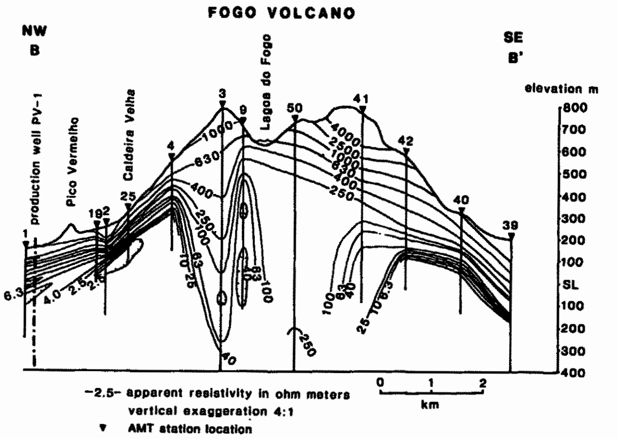

FIGURE 5
RESISTIVITY CROSS-SECTION ACROSS FOGO VOLCANO BASED ON ONE-DIMENSIONAL INVERSION OF AMT SOUNDINGS. UPWELLING OF THERMAL PLUMES IS INFERRED NEAR STATIONS NO. 4 AND 42.

to that at Sete Cidades, is clearly seen in the section; it is flanked by two zones of low resistivity. The northwest dip of the conductive layer on the north side also suggests that present production is from an outflow zone and that upwelling is occurring near sounding 4. Because of the presence of conductive rock above sea level on the south side of the mountain and its similarity to the pattern on the north side, we believe that potential exists for geothermal development on the south side of the volcano.

Conclusions

Audio-magnetotelluric surveys have proven to be particularly effective for electrical exploration in the Azores, where access, topography, and vegetation make the use of conventional controlled-source electrical methods difficult or impractical. We consider natural-source AMT surveys to be best suited for reconnaissance work, with an objective of defining target areas for more detailed surveys. Such AMT surveys are able to obtain regional or semi-regional information at lower cost and effort than controlled source methods. It is not clear, however, what would be the most cost-effective exploration program to follow our work on Fogo. The difficult terrain in the vicinity of Caldeira Velha makes further surface geophysical exploration costly.

On the three major, dormant silicic centers of São Miguel the AMT surveys identified four regions that we consider to have high to very high geothermal resource potential. The highest potential is clearly the region near Caldeira Velha, which is an extension of the present production zone into a more favorable part of the thermal system. The other areas, all previously unknown, are in the Mosteiros graben, on the south flank of Fogo near the village of Agua de Alto, (figure 4) and on the southeast flank of Furnas (figure 1).

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