GRAVITY AND RESISTIVITY SURVEYS IN HYDROTHERMAL MODELLING (S. MIGUEL-AZORES)

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ABSTRACT

Several resistivity and gravity surveys, performed in the central part of the S. Miguel (Azores) island as a contribution to built up the hydrothermal model associated to the Agua de Pau volcano, are presented in this paper.

The resistivity data inversion points out the existence of a fault system, related to a collapsed caldera, located close to the summit and in the northern flank of the Lagoa do Fogo. Through this fault system, the hydrothermal fluid would ascend and in a second phase would circulate northwards, constrained by the NNW-SSE fault system connected to the Ribeira Grande graben, towards Ribeira Grande geothermal field area. The NE-SW fault systems, crossing the above mentioned NNW-SSE one, northwards of the Ribeira Grande calderas and Pico Vermelho, would play an important role in the flow path of the geothermal fluid.

A low density body, located in the first top kilometres of the crust, suggests the existence of a geothermal reservoir, beneath the summit of the Agua de Pau volcano apparatus. So, the infiltrated meteoric would be warmed up and forced to ascend, constrained by the fault systems crossing the main edifice of the volcano.

1. INTRODUCTION

The Agua de Pau stratovolcano is located in the central part of S. Miguel island, and its summit is 947 metres above sea level. According to Moore, R. B. (1988), this volcano has a subarea volume of 80 km^3; in its caldera formed about 15200 years ago, which extends roughly 3x2.5 km is located Lagoa do Fogo.

There are several lines of physical evidence of the existence of an older caldera (7x4km) surrounding the present one. That caldera was formed, with several episodes of collapse, between 30000 and 40000 years ago. The northern, eastern and western flanks of this caldera are locally well preserved and its entire rim was well delineated by an audio-magnetotelluric survey (Hoover, D. et al., 1984).

The Água de Pau volcano complex (a geological sketch of its northern area, according to Moore, R. B., 1991, on which the E-W boundaries of the Ribeira Grande graben were implanted later *on,* is presented in fig.1) was formed by extensive Pleistocene and Holocene trachytic and mafic eruptions, dome intrusions and mudflows, occurring before and after the two calderas formation. Two historical eruptions during 1563 and 1652 were reported. *So,* the volcano would be still active, with a shallow magmatic chamber, suggested by several studies (Booth, B. et al., 1978,

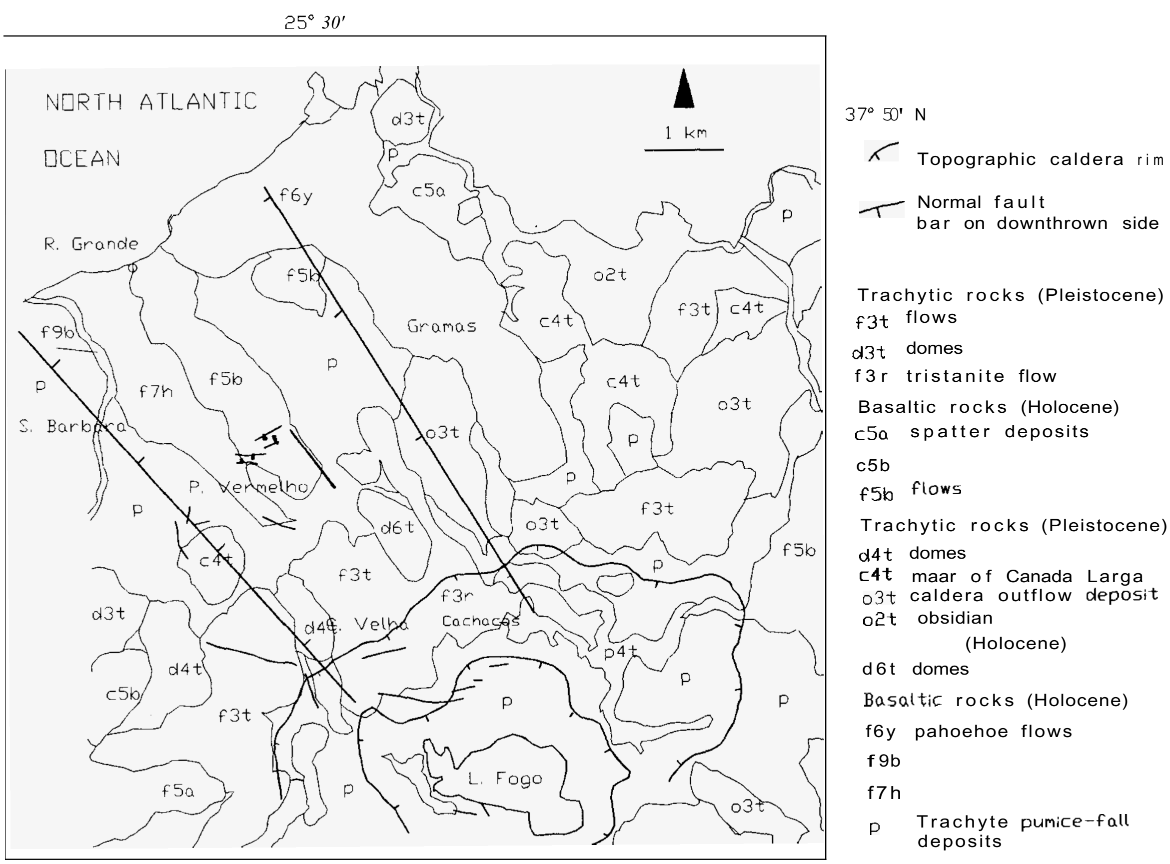

Figure 1. Geological sketch of the Ribeira Grande and Lagoa do Fogo region.

Duffield, W. A. et al., 1984, Dawson, P. B. et al., 1985).
The fault system associated to the Ribeira Grande graben, trending NNW-SSE, controls, together with the fault systems trending NE-SW and to the above mentioned older caldera rim fault, several secondary volcanic manifestations, mainly hot springs close to the boiling point, and fumaroles. Traces of fossil hot springs on the southern border of the mentioned older caldera rim, have been also detected.
In a first borehole drilled (Fig. 2) at Ribeira Grande (1973) and located 1.5 kilometers southwards of Ribeira Grande town, a temperature gradient of about 250°C/km was measured between the depth of 175 and 550 meters (Muecke, G. K. et al., 1974). The bottom temperature of this borehole reaches 200°C.
From 1976 until 1981 the research surveys carried out by Geonomics, Centro de Geofisica da Universidade da Universidade de Lisboa (CGUL), Instituto Nacional de Meteorologia e Geofisica (INMG) and Laboratório de Geociências e Tecnologia dos Açores (LGTA), led to the drilling of the boreholes RG1, RG2, PV1 and PV2 in the Ribeira Grande geothermal field.

Three boreholes (CL1, CL2 and CL3) were drilled in this new geothermal area, where temperatures up to 250° C and wellhead pressures up to 30 bars have been measured.
Another power plant (5.2 MW), was recently installed, using the steam produced by the wells CL1 and CL2. A third power plant will be also installed in this area.

2. METHODS AND TECHNIQUES

2.1. Resistivity surveys

Vertical electrical soundings (VES), dipole-dipole (DD) and pole-dipole (PD) lines and rectangles (R), were performed in the survey area.
The vertical electrical soundings were automatically inverted using a least square procedure (Johansen, 1977).
The dipoledipole and the pole-dipole lines were automatically

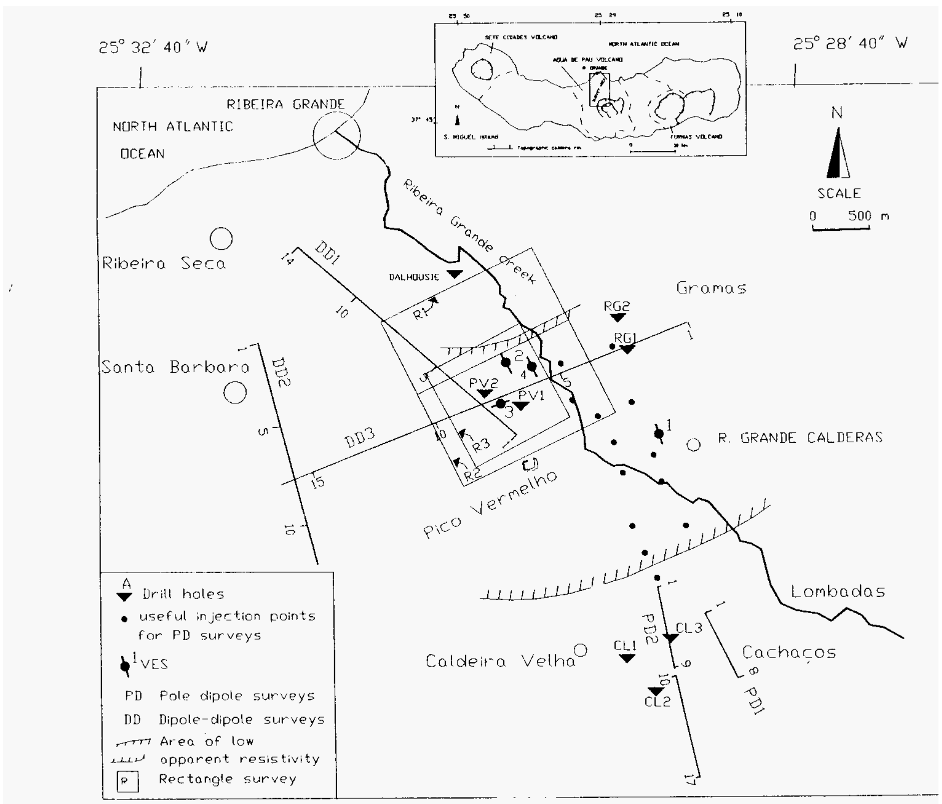

Figure 2. Surveys location.

All the wells are productive with temperatures of 225 to 235°C and at the well PV1 a 3 MW power plant was installed. However, the calcite precipitation has strongly reduced the energy production. Jonhston (1979) proposed that the geothermal heat source would be located southwards of the Ribeira Grande geothermal field, beneath the summit area of the Agua de Pau volcano. An upflow zone, connected with a fault system associated to the collapse of the above mentioned older caldera, with higher permeability and hotter (285 to 300°) geothermal fluids, and as a consequence, reducing the carbonate scaling, was then suggested (Duffield, W. A. et al., 1984).
In order to detect the above mentioned upflow zone, a resistivity survey was carried out by CGUL (1988).
Later on, this survey was complemented by a controlled source audio-magnetotelluric one, enlarging the area under study.
An existing gravity survey provided an adequate Bouguer anomaly residual map of the central area of S. Miguel, where the older caldera rim, in the north flank of the Lagoa do Fogo, is well displayed.

processed using a trial-and-error method A. Dey and H. F. Momson, 1979).

2.2. Gravity surveys

In the gravity survey (Mendes Victor, L. M. and Ribeiro, J. G., 1981), 819 measurements were performed, with the precision of .01 mGal. The altitude was determined by microbarometric levelling, whose mean error was less than 2 m. Owing to the topography, the distribution of the measurement points is irregular. The gravity net was linked to the first class international network through the station located in the Geophysical Observatory Afonso Chaves of Ponta Delgada.
The usual corrections were introduced, being the Bouguer anomaly calculated by the classic formula of reduction to the geodetic reference system of 1967.
To compute the Bouguer anomaly and to introduce the topographic corrections, the assumed density of 1.8 was deduced from the

velocity of the seismic waves using the Nafe and Drake curve and by the Nettleton method.
The Bouguer anomaly map was then filtered using a regional second degree surface, to deduce the residual anomaly map.
A gravity profile, oriented **NNW-SSE,** was inverted by a least square method, using a two and half dimensional approach (Enmark, T., 1981).

3. RESULTS

3.1. Geoelectrical surveys

The geoelectrical survey performed by Geonomics (1976) in the Agua de Pau volcano area, emphasizes the existence of a low resistivity zone (Fig. 2), located northern of the Caldeira Velha and including Pico Vermelho and Caldeiras da Ribeira Grande.
Between 1978 and 1981 the CGUL carried out in the mentioned low resistivity area, three dipoledipole lines (total length of 8.6 km), three vertical electrical soundings and two rectangular arrays. The localization of the arrays can be seen in Fig. 2.
The inversion of the dipoledipole field pseudo-sections led to the following interpretations:
DD1 - Two main low resistivity zones with 1 and 3 Ohm.m, respectively, are separated by a resistant one (300 Ohm m), in the neighbourhood of the pole 6 location. This resistive zone corresponds to the northern border of the **NE-SW** graben (fig. 1) existing in the area. The first conductive zone can be correlated to the hydrothermal circulation. This zone is located in the crossing lines of a **NNW-SSE** fault, with the above mentioned **NE-SW** fault system (the wells PVI and PV2 are located in this zone);
DD2 - In the model achieved, a fresh trachytic flow (1100 Ohm.m) is probably present. In the neighbourhood of the pole 8 location, a lateral resistivity contrast is certainly related to a fault zone moving upwards the southern block. However, no low resistivity values were detected;
DD3 - The model (fig.3) shows the boundaries of the **W-E** low resistivity area (2 Ohm.m) and points out that the wells RG1, PV1 and PV2 are located in the same geothermal reservoir. In the neighbourhood of the poles 4 and 9 of this line, the resistivity contrasts could be related to two NNW-SSE faults, crossing the **Lagoa** do Fogo area. It must be pointed out that the pole 3 location and the Caldeiras da Ribeira Grande define a lineament oriented towards Lombadas.
The models achieved from the dipoledipole lines give an overview of the localization of the **E-W** boundaries of the low resistivity zones of the Ribeira Grande geothermal field, as well as, the **N-S** ones, northwards of the Pico Vermelho location .

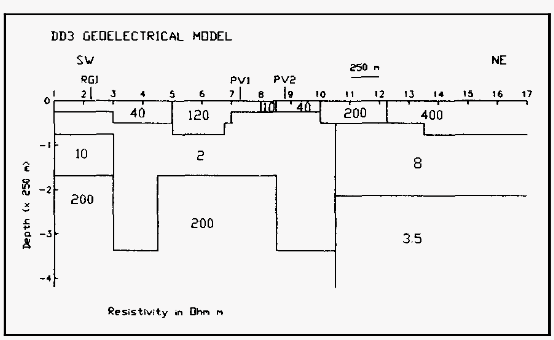

Figure 3. DD3 dipoledipole model.

A vertical electrical sounding (VES1) was carried out southwards of the localization of the well RG1. Its interpretation suggested the existence of a pumice overburden, followed by a trachytic flow; a discontinuity observed in the next branch of the apparent resistivity curve, led us to infer the existence of a fault, crossing nearly perpendicular the above mentioned lineament. This discontinuity is located in the neighbourhood of the well RG1.

The vertical electrical soundings interpretation shows more or less resistive overburden, underlain by formations whose resistivity decreases in depth, related to the presence of underground waters and altered formations by hydrothermal circulation. The lowest resistivity detected (<3 Ohm.m) is probably related to the hydrothermal circulation. The resistive basement was not reached for the longest AB12 used (1500 m).
Two rectangles (R3), with AB=2400 m and 1500 m respectively, were performed to get the detailed location of the low resistivity

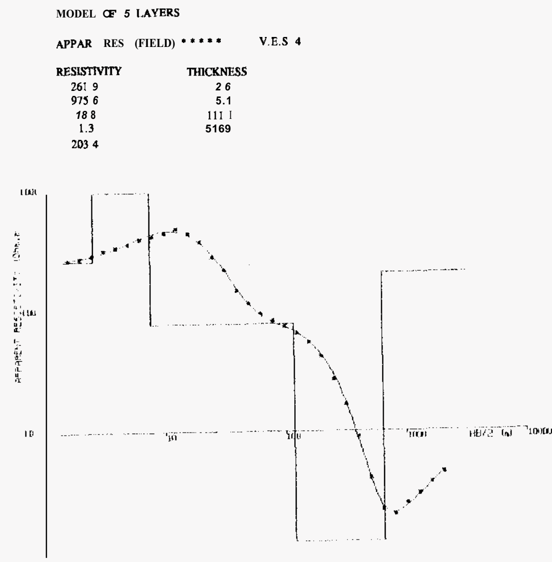

Figure **4.** Vertical electric sounding n° 4.

zones northern of the Pico Vermelho area. Later on, during 1993, this work was complemented by four resistivity rectangles, two of them with AB= 3000 m overlain (R1 and **R2)**, (fig.2) by AB= 2000 m ones, enlarging significantly the survey area. The apparent resistivity maps, whose topographic effects were removed using a three dimensional correction approach (Oppliger, G. L., 1982) suggest the geothermal fluid path.
Eastward of the Pico Vermelho, in a low apparent resistivity area meanwhile detected from these rectangular arrays, a vertical electrical sounding (VES4) was carried out. Its inversion (fig.4) was performed assuming a tabular structure and a "layer" of resistivity lower than 2 Ohm.m was detected between the depths of 120 and 600 m.
The correlation between the well stratigraphies and the resistivities obtained from the dipoledipole lines and from the vertical electrical soundings, shows at a rough guess:
- A shallow layer, with variable resistivities, most likely composed mainly by trachytic pyroclastic formations more or less argillaceous by surface alteration, as well as, by the geothermal fluids in the areas of the existing fumaroles.
- An intermediite low resistivity wne (<3 Ohm.m), formed mainly by trachytic lava flows and pyroclastic formations intensely altered by the hydrothermal fluids.
- The resistive bedrock with a basaltic and trachytic composition.
The resistivity contrasts detected suggest the existence of faults, probably coinciding with geothermal circulation zones.
To confirm the existence, in the northern flank of the **Lagoa** of Fogo, of the above mentioned upflow zone (Duffield, **W.** A. et al., 1984), two pole-dipole lines were carried out in 1988. However, in the PD1 line, owing to the topographic features of the area, the injection of the electric current for distances shorter than 850 m from the reception zone, was not possible. So, the apparent resistivity values of the overburden were not obtained. The field pseudo-sections of the pole-dipole lines, whose topographic effects were removed using a three dimensional correction approach (Oppliger, F.G., 1982) confirm the fault system above mentioned and suggest the pattern of the ascending geothermal fluid:

a) In the PD1 field pseudo-section, the pattern of the low resistivity values suggest the ascension of the hydrothermal fluid through the existing fault system and the circulation northwards and towards Lombadas.
b) The PD2 field pseudo-section, was inverted assuming a mean resistivity model for the area of the pole-dipole line out of the reception zone. The model, essentially qualitative, confirms the pattern of the ascending fluid, bounded northwards by the caldera rim and upwards by a trachytic flow. **A** pumice formation (ρ = 2000 Ohm.m) can be recognized. Between these two formations a low resistivity (200 Ohm.m) zone, probably related to the hydrothermal alteration can be seen.

3.2. Gravity survey

From east to west the residual anomaly map (fig.5), emphasizes:
a) A strong negative anomaly at Lagoa das Furnas zone, with a gradient up to 7 mGal/km. This anomaly has a strong correlation with a low seismic velocity area (Mendes Victor, L. **A.** et al., 1978);
b) The gravity gradient at Monte Escuro seems to be correlated to a tectonic feature in the NNW-SSE direction also pointed out by the above mentioned seismic survey;
c) In the central zone of the island, two negative anomaly cores at Lagoa do Fogo and Pico da Marianas and a positive one (2 mGal) separating the Ribeira Grande geothermal field area from the Lagoa do Fogo anomaly, can be seen.
The above mentioned resistivity results and those obtained from an audio-magnetotelluric survey (Hoover, D. et al., **1984),** southwards of the Caldeira Velha, were used to constrain the geometry of a model (fig.6), achieved from a gravity profile presented in figure 5.
The main features of this model are:
- **A** low density zone related to the Ribeira Grande geothermal field;
-A low density zone, trending about **ENE-SSW,** with a total extension close to **14** km, 3 km wide and 3 km thick, underlies Lagoa do Fogo and Pico da Marianas area. This model seems to be correlated to a low velocity body (Dawson, P. B. et al., **1985)** elongated about in the **W-E** direction, beneath the Agua de Pau volcano. According to these authors, the body could be 10 km long, 5km wide and 5 km thick.

4. DISCUSSION

The above mentioned low velocity and low density body, suggests the existence or a geothermal reservoir in the first top kilometres of the crust. The first order geothermal heat source could be a trachytic magma chamber (Booth, B., **1978,** Duffield, **W. A.** et al., **1984,**

S. MIGUEL Island (residual anomaly map, density 1.8 g/cm^3)

Con-tour line interval is 1 mGal

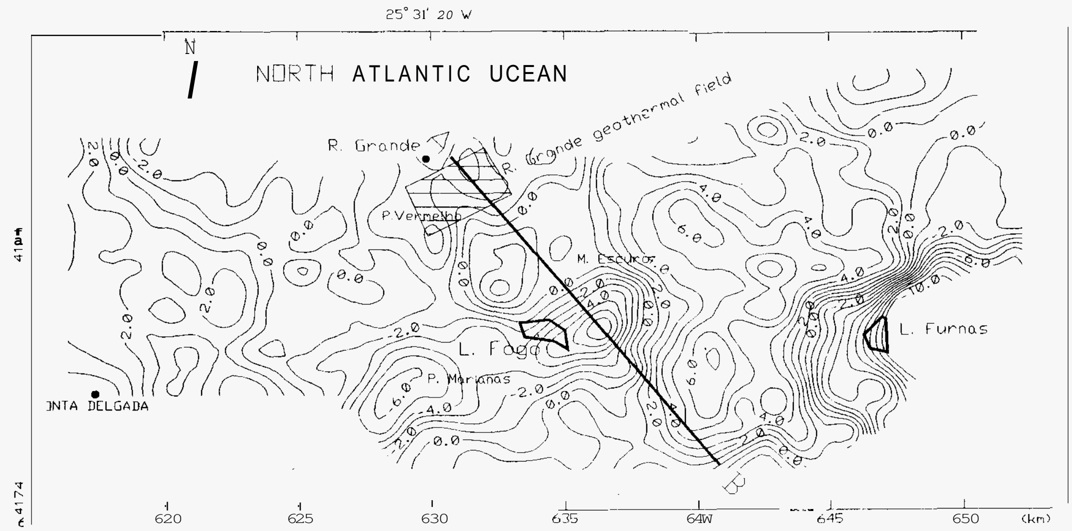

Figure **5**. Residual gravity anomaly map.

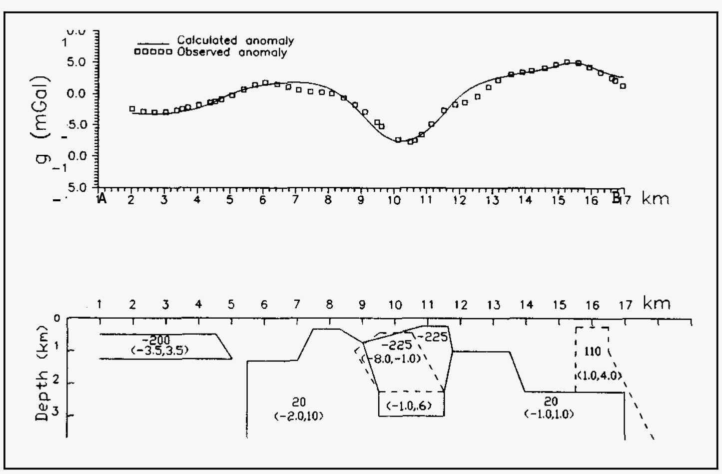

Figure 6. Gravity model.

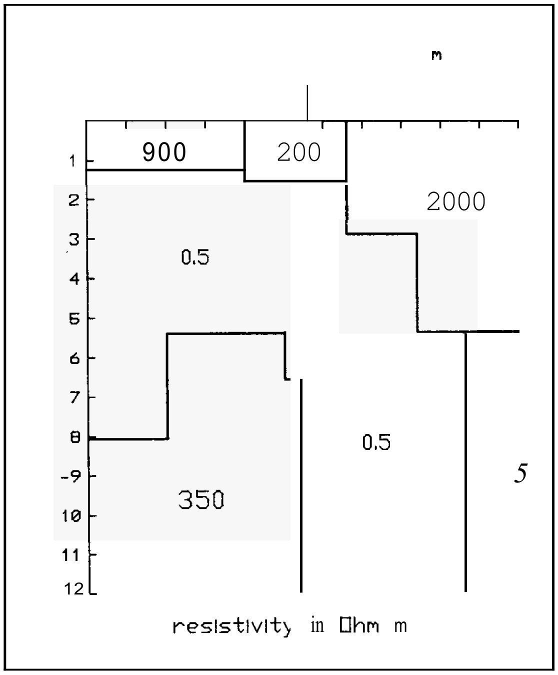

Figure 7. PD2 pole-dipole model.

Dawson, P. B. et al., 1985), beneath the summit of the Agua de Pau volcano area.

The location of the above mentioned upflow zone is coinciding with the northern boundary of the low density body and from the model we can infer a similar behaviour for the southern border.

This upflow zone suggested by Duffield, W. A. et al., (1984), seems to be confirmed by the two pole-dipole lines data. The pattern of the low resistivity values of the PD1 field pseudo-section seems to be well correlated to the assumed hypothesis.

However, the southern boundary is not well defined. The model achieved from the PD2 line (Fig. 7), is essentially qualitative, owing to the lack of data outside the reception area; however, the pattern of the low resistivity suggests the ascension and the circulation towards north of the hydrothermal fluid. In the southern boundary, a low resistivity zone (5 Ohm.m) is present, probably associated with a lower permeable zone and or with deeply altered formations. From the low resistivities measured, we can infer in the PD2 zone, higher permeability than in the PD1 one. It must be emphasized that the PD2 reception area is close to the intersection of the above mentioned fault system related to a collapsed caldera, with an important tectonic accident crossing S. Miguel island, trending **NNW-SSE.**

In the Ribeira Grande geothermal field, two **NNW-SSE** faults, probably associated with the Ribeira Grande graben, one of them in the lineament of Lombadas, Caldeiras da Ribeira Grande and RG1 well and the other one in the lineament of Caldeira Velha and PV1 well play, most certainly, an important role in the northwards hydrothermal circulation.

In the northern flank of the Pico Vermelho volcano an ascension,

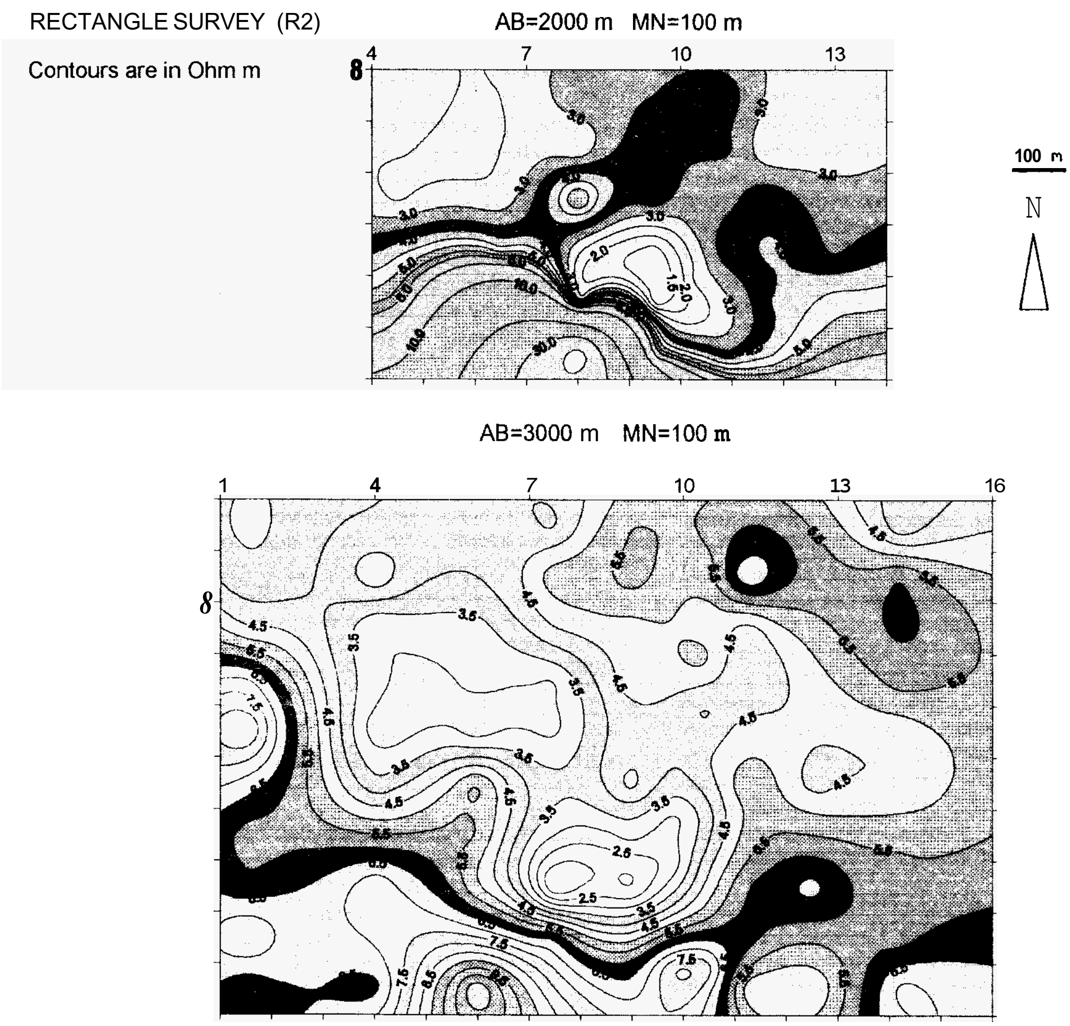

Figure 8. Apparent resistivity maps from rectangle surveys.

through a narrow area, of geothermal fluid is suggested by the low apparent resistivities (<2 Ohm.m) measured, in two overlain rectangular (R2) arrays, with AB=3000 m and **AB=2000** m (Fig. 8), respectively. In a second phase, the geothermal fluid would flow northwestwards (the wells PV1 and PV2 are located inside this zone).

Meanwhile, high permeable zones are linked to the crossing lines of the above mentioned **NNW-SSE** faults with fault systems nearly perpendicular to these ones. One of these high permeable zones is coinciding with the low resistivity area displayed by the above mentioned R2 underlain rectangular arrays. The other one is located in the crossing zone of the fault detected by VES1 and by the above mentioned Lombadas, Caldeiras da Ribeira Grande and RG1 lineament. All the boreholes drilled in the Ribeira Grande geothermal field are located in these zones.

5. CONCLUSIONS

A geothermal reservoir will be probably located in the first top kilometres of the *crust,* beneath the summit area of the Água de Pau volcano apparatus. A trachytic magma chamber was suggested as a first order heat source for the above mentioned geothermal reservoir.

From the achieved data, at least two upflow zones seem to be located within the survey area, correlated to the crossing lines of the existing fault systems. We could assume that the infiltrated meteoric waters would be warmed by the heat released from the above mentioned trachytic magma chamber. The geothermal fluid would ascend through fractured zones. and then would be spread, constrained by the permeability of the pyroclastic and of the lava flow formations, as well as, by the existing fractures. The major fault systems, and namely the fault systems associated with the Ribeira Grande graben, would play an important role in the flow path of the geothermal fluid.

In the southern flank of the Lagoa do **Fogo** a similar behaviour is expected, but more survey works are necessary to confirm this hypothesis.

REFERENCES

Booth, B., Croasdale, R. and Walker. G.P.L., (1978). A quantitative study of five thousand years of volcanism on S. Miguel, Azores. ***Trans.*** R ***Soc. London,*** 288, 271,319.

Dawson, P.B., da Silva, A.M.R., Iyer, H.M., Evans, J.R. (1985). Seismic study of the Agua de Pau geothermal project, S. Miguel, Azores. ***Geothermal Resources Council Transactions,*** Vol. 9, pp.401-405.

Dey, A. and Morrison, H.F. (1979). Resistivity modelling for arbitrarily two dimensional structures. ***Geophysics,*** 27, pp. 106-136.

Duffield, W. A., and Muffler, L.J.P. (1984). Geothermal Resources of S. Miguel Island, Azores, Portugal, ***USGS Open-file Report 84-287, 21 p.***.

Enmark, T., (1981). A versatile interactive computer program for computation and automatic optimization of gravity models. ***Geoexploration,*** 19, pp. 47-66.

Hoover, D., da Silva, A.M.R., Pierce, H., Amaral, R. (1984). The application of audio-magnetotelluric surveys on S. Miguel island, Azores, Portugal. ***Geothermal Resources Council Transactions,*** Vol. ***8,*** pp.499-503.

Johansen, H.K. (1977). A man/computer system for resistivity soundings over a horizontally stratified earth. ***Geophysical Prospecting,*** Vol. 27, pp.667-691.

Johnston, D. (1979). ***Geothermal Resources of Portugal.*** Unpublished Report prepared for U.S. Dept. of Energy.

Mendes Victor, L.A., Forjaz, V.H., Him, A. (1978). Explosion Seismology on S. Miguel and Terceira (Azores). EOS, 59, pp. 321.

Mendes Victor, L.A. and Ribeiro, J.G. (1981). Estudos gravimétricos no Arquipélago dos Apres e análise do campo gravítico na ilha de S. Miguel, entre 25° 20' e 25° 40'W. ***Revista do Instituto Nacional de Meteorologia e Geofísica,*** Lisboa, pp. 3-39.

Moore, R.B. (1988). Geology of the late quaternary stratovolcanoes on S. Miguel, Azores. ***US. Geological Survey Bulletin,*** 1900.

Muecke, G.K., Ade-Hall, J. M., Aumento. F., MacDonald, A., Reynolds, P.H., Hyndman, R.D., Quintino, J., Opdyke, N., Lowrie, W. (1974). Deep drilling in an active geothermal area in Azores. ***Nature,*** Vol. 252, Nº 5481, pp.281-285.

Oppliger, G.L. (1982). ***Three dimensional terrain effects in electrical and magnetometric resistivity surveys.*** Ph. D. Thesis, Univ. California.