GEOPHYSICAL SURVEY OF THE PICO ALTO GEOTHERMAL PROSPECT, TERCEIRA ISLAND, AZORES

Errol Anderson, Greg Ussher and Kevin Tearney

Geothermal Energy New Zealand Limited
Auckland, New Zealand

ABSTRACT

A geophysical study has been made of the Pico Alto Geothermal Prospect located within the caldera of Guilherme Moniz Volcano on the island of Terceira. Gravity surveys have outlined major structural trends and located the outer boundary of the Caldera. The Furnas do Enxofre hydrothermal area lies within the complexly faulted western Caldera margin. The Caldera has a surface area of 25 km^2 and is infilled to a depth of 1100m below sea level. Resistivity traverses and soundings indicate hydrothermal alteration of caldera infill to a mean level of 200m rising to 450m at Furnas do Enxofre. Present geothermal fluid levels are Snferred to be at about sea level. Probable outflows are recognised to the north and north-east. A regional Self-potential high over the area is indicative of a deep geothermal system. Caldera faults which correllate with short wavelength SP highs are inferred to be preferred conduits for ascending geothermal fluids. Magneto-telluric results indicate low resistivities associated with hot, essentially dry, hydrothermally altered rocks at 3 to 5km below the Caldera.

INTRODUCTION

The Pico Alto Volcanic Centre (PAVC), Terceira, has been investigated by an 8 month programme of geophysics undertaken during 1981-82 (Anderson et al 1982). PAVC forms a complex pile of young trachyte volcanics which occupy the northern part of the large Pleistocene age caldera of Guilherme Moniz Volcano in the centre of the Island (Collis 1982). The small hydrothermal area of Furnas do Enxofre (6500m^2) lies on the western periphery of the caldera.

GRAVITY SURVEYS

A network of 182 regional stations was established on Terceira to evaluate the regional gravity field. A further 121 stations were occupied along four surveyed profiles located across PAVC. Gravity stations were tied in to the International Gravity Base Station IGB 11875 at Lajes Air Base. Data were reduced to absolute Free Air and absolute Bouguer anomalies with sealevel datum. 'Basement' density of 2.67 Mgm^{-3} and seawater density of 1.03 Mgm^{-3} were used for the Bouguer reduction. Because of the great depth of ocean surrounding Terceira, terrain corrections were calculated using the line integral method of Bott (1959) to at least 45km from each gravity station. Average error in terrain correction is estimated to be ±0.5 mgal.

The observed regional Bouguer anomaly is shown by Figure 1. Maximum value of the gravity field is about 129 mgal. The NW-SE and W-E regional gravity trends dominate the Bouguer anomaly field and reflect the two major structual elements of the Island (i.e. the Terceira Ridge and the Central Rift Zone; Lloyd and Collis 1981). A major gravity low is associated with Guilherme Moniz Caldera.

An estimate of the first order regional field was made using a polynomial trend surface fit method (Dougenik and Sheehan 1977). Only observed Bouguer anomaly values at coastal stations around the Island were used to constrain the trend surface, thereby minimising the influence of observed gravity lows on the resulting polynomial. A second order trend surface was chosen to represent this field (Figure 2.).

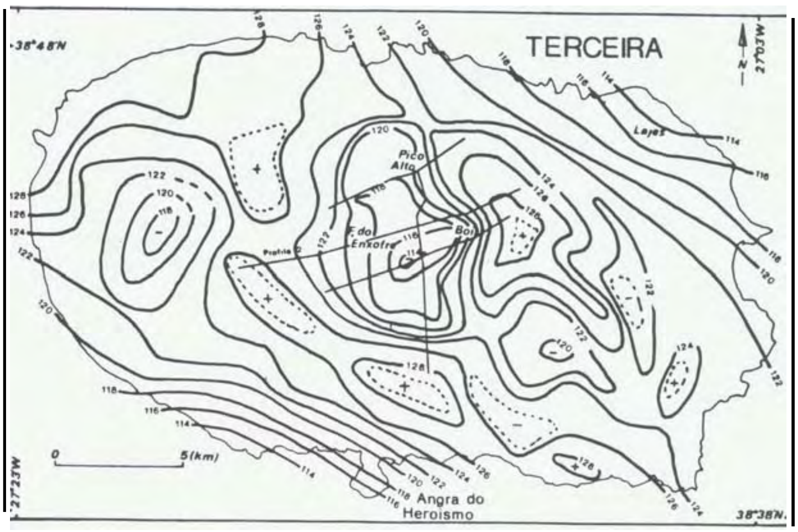

Figure 1. Observed Bouguer Anomaly (mgal)

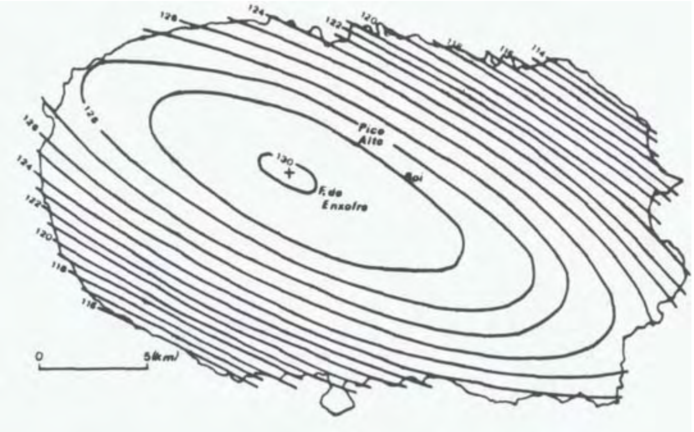

Figure 2. First order regional gravity field (mgal)

Residual Anomalies

The residual anomaly over Guilherme Moniz Caldera (Figure 3.) has a minimum value of -16 mgal. Steep horizontal gravity gradients of 6-8 mgal/km are peripheral to this gravity low except over Furnas do Enxofre where the horizontal gravity gradients are significantly less steep (2-3 mgal/km). The symmetry of the anomaly pattern is highly distorted over Boi. The gravity low is caused by the density contrast between the low density caldera infill and the more dense surrounding rocks which form the bulk of Guilherme Moniz volcano. The depressed horizontal gravity gradients over the inferred western margin of the caldera reflect the gravitational effect of the Central Rift Zone. The two gravity highs adjacent to the caldera are remnants of the regional gravity field. These remnants disturb the residual anomaly patterns.

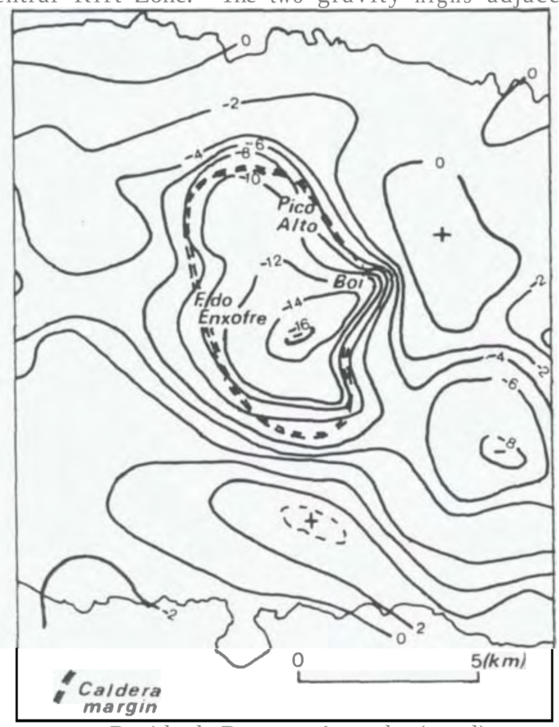

Figure 3. Residual Bouguer Anomaly (mgal)

Anomalies from gravity stations along the four surveyed profile lines across the caldera were interpreted in terms of 2-dimensional density bodies using the method of Talwani et al (1959).

The density structure of the models was partly constrained by measured surface rock densities. For the bulk of the Island we assigned a representative density of 2.6 Mgm^{-3}. The average density of the caldera infill is poorly known. We estimate an average density of about 2.3 for this material above sealevel, increasing to a density of about 2.4 from sealevel to the caldera base. An error of 1 mgal was tolerated in the model calculations over undisturbed sections of the anomaly curves. Model section for Profile 2 is shown in Figure 4. The boundary of Guilherme Moniz Caldera as determined from the model computations as given in Figure 3.

The western margin of Guilherme Moniz Caldera is a fault zone. The outer limit of the fault zone lies about 1 km west of the boundary faults mapped by Lloyd and Collis (1981). This fault zone is largely buried by post caldera collapse volcanic material and has limited surface expression. Collapse scarps inside the inferred margin indicate that successive caldera collapse has occurred. Furnas do Enxofre lies within the fault zone (i.e. within the Caldera).

The eastern margin of the Caldera may be less complex. The position of the Caldera boundary defined by the gravity models closely corresponds to the margin mapped by Lloyd and Collis (1981). This margin trends NNW from Boi Volcano. Three-dimensional structural complexities near Boi lower the precision with which this margin can be positioned.

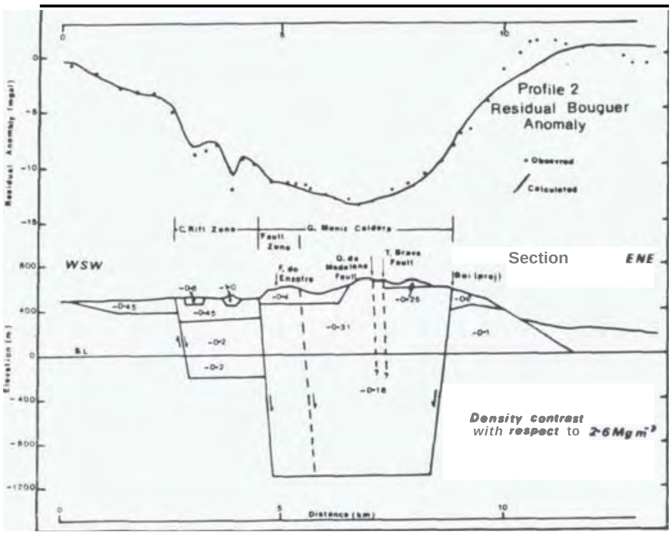

Figure 4. Model section, Profile 2

Guilherme Moniz Caldera as defined above has a total surface area of about 25km². The boundary faults dip at 75° - 85° into the Caldera. The base of the low density caldera infill lies at average depth of 1100m below sealevel. Assuming a mean elevation of 500m for the upper surface of the infill yields a total volume of this material of approximately 40 km³.

RESISTIVITY SURVEYS

Resistivity traverse measurements were made at over 120 stations across the prospect area using Schlumberger arrays (AB/2 = 500m and 1000m). Major resistivity regimes were further investigated by 14 Schlumberger soundings made to AB/2 = 2000m or greater. Large current arrays were necessary because of the thickness of resistive overburden indicated by the traverses. "Mini Soundings" of AB/2 spacings up to 315m were made at selected traverse stations using three points per decade. These were combined with the previously obtained traverse resistivity values to give an effective spread to AB/2 = 1000m. These soundings could be executed relatively quickly (2 - 5 per day) and proved to be an efficient method of extending resistivity modelling.

The non-homogeneous nature of the volcanic terrane introduced some problems with sounding curve interpretation. AC coupling effects became significant when larger arrays (AB/2 > 1000m) were used in low resistivity areas (Hochstein et al, 1982) so true resistivities of the deeper layers could not be determined unambiguously. Soundings were initially modelled using 2 layer (Keller and Frischknecht 1979) and 3 layer (Koefoed 1979) curve matching techniques. These models were modified by an automatic optimization technique. Where applicable, resistivities were then standardized and the models correlated with known geology and hydrology and re-optimized (Figure 5).

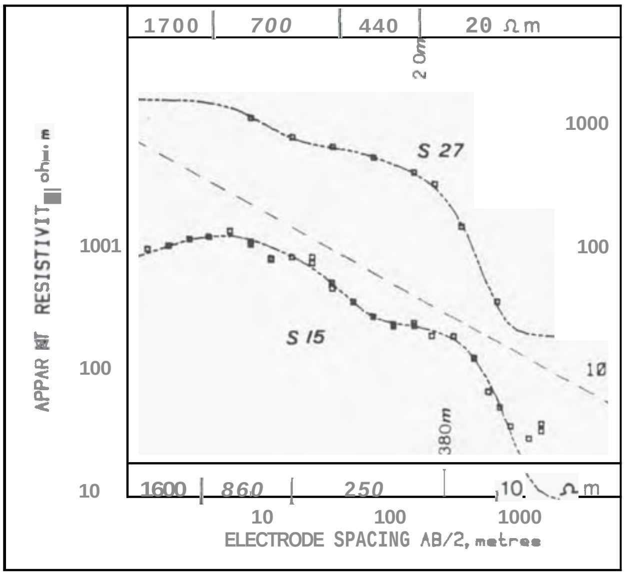

Figure 5. Sounding curves and computed models for sounding 515 and mini-sounding 527. 515 is modelled on the curve section up to AB/2 = 1200m

An elongate region of low apparent resistivity coincides with the western boundary fault zone of the Caldera (Figure 6). The lowest apparent resistivities in this zone (10Ωm measured with the AB/2 = 1000m array) are found near the Furnas do Enxofre thermal area. This region is sharply bounded to the west by the basaltic shield of Santa Barbara volcano which is characterized by high apparent resistivities. A second area of low apparent resistivity is found in the lowland to the east of the Caldera. An IP anomaly probably associated with the Serra do Cume Fault was detected in this area by the traverse survey. The southern part of the Caldera is a sizeable groundwater reservoir and is marked by moderate apparent resistivities of 50Ωm to 100Ωm. High apparent resistivities are characteristic of the substantial thicknesses of young trachytic lavas over PAVC.

Soundings indicate that a low resistivity layer exists at depths of 200m to 450m beneath the Caldera and extends laterally to the coast in the north and north-east. This layer reaches a maximum level of 450m at Furnas do Enxofre (Figure 7). The depths to marked temperature increase in temperature gradient holes at Furnas do Enxofre correlate with the level of the low resistivity layer. Resistivities of less than 20Ωm within the caldera suggest that there has been some mineralisation of the Caldera infill, probably by hydrothermal alteration. Ancient sinter deposits at 150m and 300m elevation in the north (Lloyd and Collis 1981) correlate with the level of inferred alteration.

Thermal fluids must have been present to a level of about 300m in much of the northern half of the Caldera. These fluids were able to rise along the fault zone that marks the Caldera's

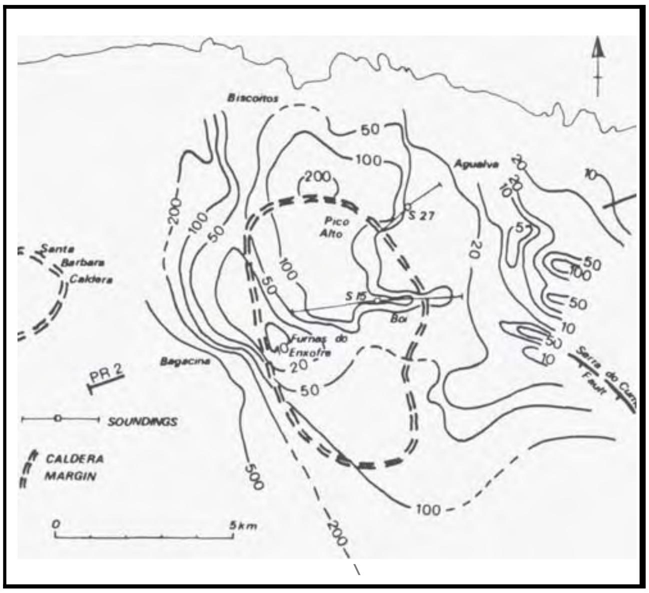

Figure 6. Apparent Resistivity, AB/2 = 1000m

western boundary where alteration has reached its highest level. Ambiguity in sounding interpretation of the low resistivity layer can allow resistivities to be much lower than indicated in the models. It is therefore possible that thermal fluids (of low resistivity) are still present at the level indicated by the top of the low resistivity layer. However, there are no thermal water outflows at present found on Terceira and no anomalous temperature gradients are found outside the Enxofre thermal area (except TG8 which showed a marked temperature increase during drilling, Figure 7). It is therefore inferred that any thermal water levels are lower now than in the past. The lowest resistivities of 3Ωm found at S3 (Portal das Rossas) and S29 (Aqualva Sawmill) indicate a present fluid outflow at about sea level from the Caldera to the north-east. The traverse maps indicate that a similar outflow may exist or has existed to the north from the region of Furnas do Enxofre.

SELF-POTENTIAL SURVEY

Self-potential (SP) measurements were made at resistivity traverse stations prior to resistivity measurements. The SP array consisted of copper - copper sulphate porous pot electrodes at 500m spacings. Traverse cables were used to connect the electrodes. Insitu verification of 500m array self-potentials was achieved by comparison with 1000m array data also recorded. SP profiles formed a network of small (second order) and larger (first order) loops across the prospect. This network was arbitrarily referenced to zero at Bagacina. Loop closure errors after error distribution are of the order of ± 20mV.

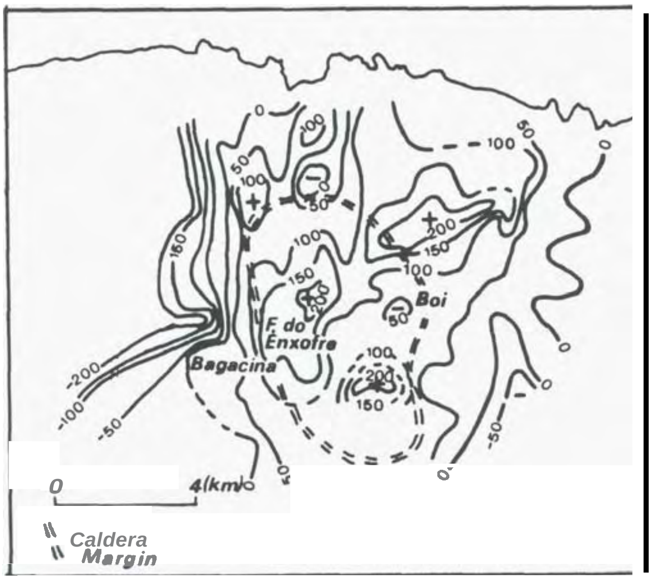

Figure 8. Self-potential Anomaly (mV)

A broad regional SP high is observed over the region (Figure 8). Steep horizontal SP gradients of 150 - 200mV/km coincide with the lateral resistivity boundary west of the Caldera; in the east, horizontal gradients are much less steep and reflect the more gradational lateral resistivity changes observed in this area. The fault zone which forms the western Caldera margin is marked by SP highs closing at 100mV in the north and 200mV NE of Furnas do Enxofre. The Furnas do Enxofre hydrothermal area lies within the 150mV

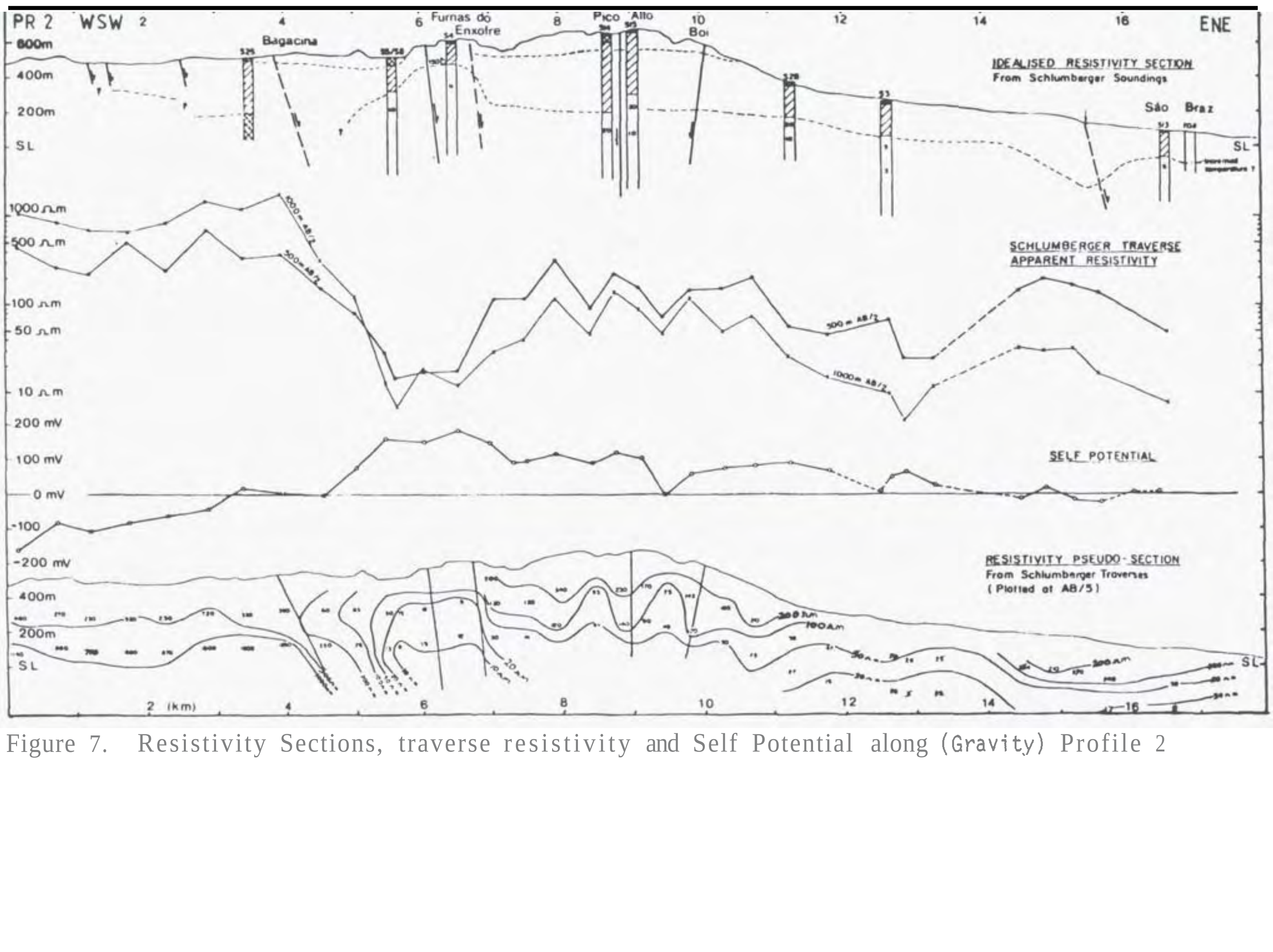

Figure 7. Resistivity Sections, traverse resistivity and Self Potential along (Gravity) Profile 2

contour along a positive anomaly belt which trends NE over the Caldera. The trend axis of this anomaly belt coincides with the position and orientation of major recent faulting. A high closes at 200mV over the inferred intersection of two .major Caldera faults in the SE.

The regional high over the Caldera may be indicative of a deep geothermal system (Corwin and Hoover **1979)**. The positive short wavelength anomalies reflect major fault trends and tend to correlate with areas of low resistivity **(e.g.** Furnas do Enxofre, Figure **7)**. We infer that these faults are acting as preferential conduits for geothermal fluids. Positive anomalies within the Caldera indicate major centres of upf1owing fluids; the elongate high outside the Caldera probably represents lateral flow of these fluids towards the **NE** coast. The two closed negative **anomalies** may indicate the descent of cooler fluids into the geothermal system.

MAGNETO-TELLURIC SURVEY

A magneto-telluric survey comprising 100 sites **was** carried out on Terceira between February and April **1982.** Magnetic variations in three orthogonal directions were measured using **fluxgate** magnetometers, and the telluric field using copper-copper sulphate porous pot electrodes. At each site, measurements were made at sampling intervals *of* **0.5s** and **0.1s,** obtaining a data set ***of*** 1024 values for each. The overall frequency range is thus from .002 **Hz** to **5 Hz.**

Analysis

The data was analysed at Victoria University of Wellington using programs developed by the Physics Department. The coefficients relating the magnetic and telluric fields were estimated by the harmonic analysis method using a least-squares **fit** over chosen frequency bands (Porstendorfer 1975). From these values, apparent resistivities and directions of anisotropy were calculated.

Because of the impulse nature of the incoming electromagnetic signal (Illiceto and Santarato **1979),** and to minimise errors from noise, **it** is essential to select frequency bands containing a significant signal level. To do this, the Fourier auto-powers for each component and the cross-powers for each component and the cross-powers between the components were calculated and listed for a closely-spaced set of narrow frequency bands. These values were inspected and frequency bands with high power and good correlation between orthogonal magnetic and telluric components were selected.

To further ensure reliable results, the apparent resistivities and rotation angles were calculated by two methods, one using impedances and the other with admittances (Gamble et **al**, 1979). The results of a particular frequency band were used only **if** values calculated by each method were sufficiently close.

As the behaviour of the transfer matrix under rotation can give an **indication** of the **2- or 3-** dimensional nature of the subsurface, the matrix elements were listed at **15** intervals and inspected. Also the three magnetic components were used to calculate Parkinson Vectors (Bromley **1979),** a method that can indicate the presence of good subsurface conductors.

Interpretation

In general, unreliable results were obtained at the higher frequencies of the range, presumably because the incoming signal at these frequencies is small. Because of this, unambiguous interpretation of apparent resistivity curves in terms of layered models has not been possible. However, estimates of the total conductance to the highly resistive basement have been made at a number of sites (Figure **9)** by using the steeply-rising part of the curve (Porstendorfer **1975).** The higher conductance over PAVC has been tentatively assumed to be caused by hot, **al**tered, essentially dry rock, 2 to 3 km thick, and extending to a depth of about **5km,** with a resistivity of **1-3Ωm.** Such a structure has been observed in New Zealand (Hochstein and Bromley **1979).**

Sites within or near to PAVC generally show large resistivity anisotropies, rapidly varying directions of strike with frequency, and a complex subsurface resistive structure, whereas, at more distant sites, a more layered and isotropic structure is indicated.

The results of the Parkinson Vector analysis are not particularly definitive but enhanced magnitudes are observed near to PAVC, particularly towards the north-east. These also suggest a conductive structure under the Caldera.

The complex structure of an island such as

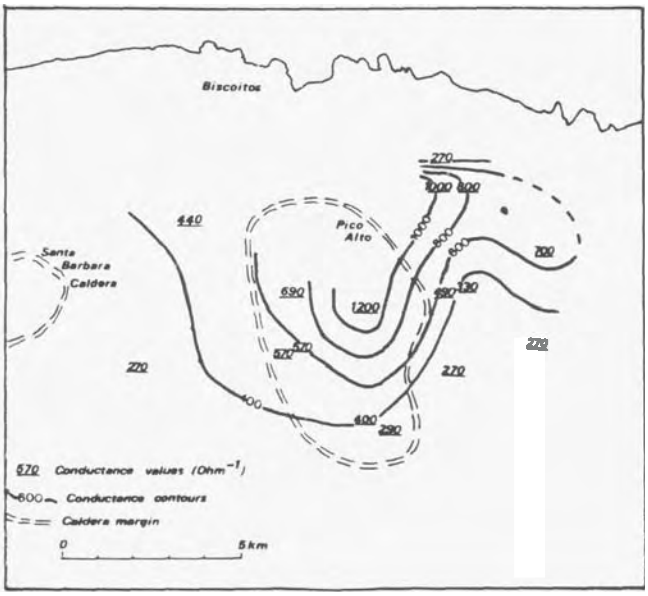

Figure 9. Total Conductance to highly resistive basement

Terceira tends to limit the usefulness of magneto-tellurics as an interpretative method but the results do confirm and reinforce the results of Schlumberger traverses and soundings.

The equipment used in this survey is particularly portable, an advantage in rugged terrain, but has a poor signal-to-noise ratio at higher frequencies. Analysis is continuing in an attempt to extract useful data at these frequencies.

CONCLUSION

Guilherme Moniz Caldera has a surface area of about 25 sq km. The Caldera is structurally complex. It is infilled by about $40km^3$ of relatively low density pyroclastics and higher density volcanic lava flows. These rocks are the products of caldera collapse and resurgent volcanism. The lower limit of the Caldera infill (i.e. the base of the Caldera) lies at an average depth of about 1100m below sealevel. The western margin of the Caldera is a complex fault zone.

A deep geothermal system probably exists beneath the Pico Alto Volcanic Centre in the northern part of the Guilherme Moniz Caldera. We tentatively identify at least two areas where geothermal fluids are ascending from depth. These areas are associated with major Caldera faults. The hydrothermal field at Furnas do Enxofre lies within the fault zone of the western Caldera margin in an area affected by a high degree of secondary faulting.

Geothermal waters are probably present to at least sealevel beneath the Pico Alto Volcanic Centre and, in the past, reached an average level of about 300m; at Furnas do Enxofre geothermal waters reached a level of at least 450m. Geothermal fluids probably outflow from the Caldera to the north and north-east and presently discharge below sealevel. No probable outflows are identified to the west or south of the Caldera.

Low resistivities of 1-3Ωm occur at depth (3-5km) below the Caldera and probably extend towards the north east. These resistivities are considered to be associated with hot, essentially dry, hydrothermally altered rocks. These rocks lie at a greater depth than the main geothermal fluids reservoir.

ACKNOWLEDGEMENT

We thank the Laboratorio de Geociencias e Tecnologia, Acores for permission to present these geophysics results of this survey.

REFERENCES

Anderson, E., Ussher, G., and Tearney, K., 1982: Gravity Survey, Geothermal Prospection - Ilha Terceira, Acores. unpub. report, Geothermal Energy New Zealand Limited.

Bott, M.P.H., 1959: The use of electronic digital computors for tne evaluation of gravimetric terrain correction. Geophysical Prospecting VII. 45-53.

Bromley, C.J., 1979: Geomagnetic depth sounding and magneto-telluric survey of the Southern Alps. MSc thesis, Victoria University of Wellington.

Caldwell, G., Hochstein, M.P., Befekadu Oluma, 1982: AC effects in resistivity data from geothermal prospects. Proceedings of the New Zealand Geothermal Workshop 1982.

Collis, S.K., 1982: Geology of the Pico Alto geothermal prospect, Terceira Island, Azores. Proceedings of the New Zealand Geothermal Workshop 1982.

Corwin, R.F. and Hoover, D.B., 1979: The self potential method in geothermal exploration. Geophysics 44: 226-245.

Dougenik, J.A. and Sheehan, D.E., 1977: SYMAP User's Reference Manual. Laboratory for Computer Graphics and Spatial Analysis, Graduate School of Design, Harvard University.

Gamble, T.F., Gouban, W.M. and Clarke, J., 1979: Magnetotellurics with a remote magnetic reference. Geophysics 44: 53-68.

Hochstein, M.P., and Bromley C.J., 1979: Resistivity structure of the Tongariro Thermal System, North Island, New Zealand, in proceedings of the New Zealand Geothermal Workshop, Part 1: 20-29.

Iliceto, V. and Santarato, G., 1979: A new attempt at automatic data processing in magneto-tellurics. Geoexploration, 17: 19-32.

Keller, G.V. and Frischknecht, F.C., 1979: Electrical methods in geophysical prospecting. Pergammon Press Inc. Oxford: 523.

Koefoed, O., 1979: Geosounding principles, 1, Resistivity sounding measurements. Elsevier, Amsterdam: 276.

Lloyd, E.F. and Collis, S.K., 1981: Geological report, Geothermal prospection - Ilha Terceira, Acores. unpub. report, Geothermal Energy New Zealand Limited.

Porstendorfer, G., 1975: Principles of magneto-telluric methods. Geoexploration Monographs, 1, No. 5, West Berlin, Gebruder Borntraeger.

Talwani, M., Worzel, L. and Landisman, M., 1959: Rapid gravity computation for two-dimensional bodies with application to the Mendoncino submarine fracture zone. Journal of Geophysical Research 64: 49-59.