A MAGNETOTELLURIC SURVEY IN A REPORTED GEOTHERMAL AREA IN SOUTHERN PORTUGAL

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ABSTRACT

A geothermal anomaly with heat flow density (HFD) values of about 200 mW/m^2 near its center has been reported to exist in southern Portugal. The area where the anomaly is claimed to occur is geologically complex and is crossed by two major tectonic features: the Messejana fault and the Ferreira-Ficalho overthrust. A magnetotelluric (MT) survey was carried out in the region of the highest reported HFD values with the intent of delineating the anomaly in electrical terms and understanding its origin. Thirty-four MT sites were occupied over an area of about 2,500 km^2 and, after processing the MT data, electrical resistivity maps at several depths were constructed. Interpretation of the processed data indicates that the HFD values reported for the area of the MT survey do not represent the thermal state of the upper crust in the region. However, low electrical resistivity values are found in zones that coincide at the surface with the Messejana fault and the Ferreira-Ficalho overthrust. This may indicate that fluid flow occurs within these two tectonic features and may generate local high HFD values near the surface.

INTRODUCTION

One of the first attempts to compile geothermal data collected in Portugal up to 1987 was published in the "Atlas of the Geothermal Resources in the European Community, Austria and Switzerland" as a heat flow density (HFD) map for southern Portugal (Haenel and Staroste, 1988). The main feature of that map is a geothermal anomaly, known as the Alentejo Geothermal Anomaly (AGA), with HFD values as high as 160 mW/m^2 in an area centered at about 38°10'N and 8°0'W (see Fig. 1). Subsequent work by Duque (1991) and Duque and Mendes-Victor (1993) confirmed the general trends indicated in the map and the existence of the geothermal anomaly reported in the atlas. They suggested, based on additional corrections applied to the geothermal data and several additional HFD determinations, that the HFD values for the central region of the AGA are as high as *200* mW/m^2. The heat flow density values were calculated by measuring the temperatures at several depths in mining wells that were thought to have reached thermal equilibrium, and multiplying the geothermal gradients obtained in that way by the thermal conductivities measured on rock samples from cores from the same wells. A more detailed description of the geothermal data set can be found in Correia *et al.* (1982), Duque (1984), Duque (1991) and Correia *et al.* (1993). To constrain the HFD values calculated for the AGA, chemical analyses were performed on rock samples collected in some of the geological formations that outcrop in the AGA region to estimate regional heat production rates (Correia *et al.*, 1993). Recently, Almeida (pers. commun., 1991) and Almeida (1990, 1993) have presented some new geothermal data obtained in southern Portugal in an area that includes the area of the MT study. His results indicate lower HFD values than those previously reported with values that range between 60 and 90 mW/m^2.

It is well established that temperature affects most of the physical parameters of rocks, and, in particular, the electrical conductivity or, its inverse, the electrical resistivity. The fact that the bulk electrical conductivities of rocks increase with temperature suggests that electrical methods should be well suited to determine or infer the electrical structures of high HFD regions where high electrical conductivity anomalies (or low electrical resistivity anomalies) are expected to coincide with the high HFD anomalies.

With this in mind, a geoelectrical survey using the magnetotelluric (MT) method was performed over the AGA with the objectives of delineating its geoelectrical structure and understanding its geological and geophysical characteristics within the regional geological framework. It should be noted that the AGA has not been detected by any other geophysical method than the geothermal method. Therefore, it was hoped that, because of the relationship between temperature and electrical conductivity (or resistivity), the magnetotelluric survey over the geothermal anomaly could shed some light on the thermal state of the Alentejo Geothermal Anomaly.

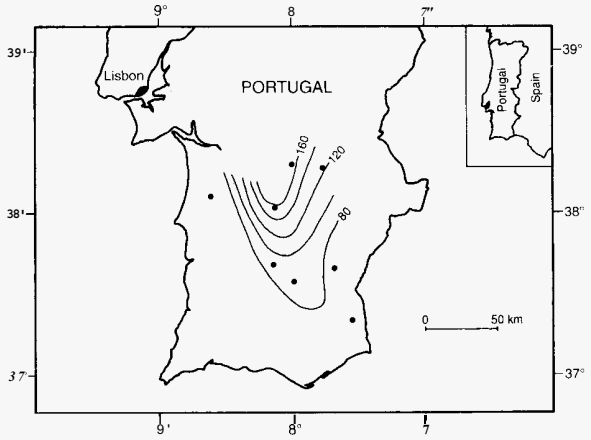


Figure 1. Heat flow density for southern Portugal. Contours in mW/m^2. The dots indicate the locations of the heat flow density measurements (redrawn from Haenel and Staroste, 1988).

GEOLOGIC SKETCH OF THE STUDY AREA

According to Ribeiro *et al.* (1979) and Julivert *et al.* (1980), the core of the Iberian Peninsula is an Hercynian cratonic block, bordered to the northeast and southeast by segments of the Alpine belt (Pyrenean and Betic orogens) and to the northwest, west, and southwest by the Atlantic Ocean. The Hercynian belt outcrops in the western part of Iberia, forming what is known as the Hesperian or Iberian Massif; to the east it plunges gently under a Meso-Cenozoic platform cover. The Iberian Massif is crossed by Hercynian structures trending NW-SE and to the north describes an arc known as the Ibero-Armorican arc.

The Iberian Massif exhibits a longitudinal zonation, as in many other European Hercynian massifs, and is divided, from north to south, into five geotectonic units: Cantabrian, West-Asturian-Leonese, Central Iberian, Ossa-Morena, and South-Portuguese zones. These zones are generally separated by deep first order tectonic features.

The Iberian Hercynian belt also shows a fan-like pattern with steep structures in the core and outward vergences in the margins. In its southwest branch (the region of the MT study) the contact between the internal and external zones (corresponding to the Ossa-Morena and South-Portuguese zones) coincides with a major overthrust known as the Ferreira do Alentejo-Ficalho overthrust (from now on called the Ferreira-Ficalho overthrust), which trends approximately NW-SE (see Fig. 2).

The Ossa-Morena zone is characterized by Precambrian and Lower Paleozoic rocks showing intense deformation and widespread plutonism and magmatism. As the Ferreira-Ficalho overthrust is approached from the NE, basic and ultra-basic rocks are more common than granitic rocks. On the other hand, the Upper Paleozoic is more fully developed in the South-Portuguese zone where there is little plutonism and the metamorphism is low grade and where there are also some volcanic and sedimentary deposits that were deformed during the Hercynian orogeny.

The study area is also crossed by another major tectonic feature known as the Messejana fault. This left lateral strike-slip fault cuts and offsets, up to 4 km, Hercynian structures, and trends approximately NE-SW. The Messejana fault begins in the Atlantic Ocean, traverses the whole of southern Portugal, and disappears in Spain beneath Tertiary formations. Its origin seems to be related to the opening of the Atlantic Ocean in Early to Middle Triassic times (Schermerhorn *et al.*, 1978). A doleritic dyke system was emplaced along the Messejana fault by a multiple intrusive process during Early and Middle Jurassic and possibly starting in late Triassic.

Fig. 2 is a simplified geological map of the area where the magnetotelluric survey was performed. Also shown are the locations of the Messejana fault and the Ferreira-Ficalho overthrust, as well as the locations of the MT sites. The area covered by the magnetotelluric survey is approximately 2,500 km^2 and has little topographic variation.

THE MAGNETOTELLURIC SURVEY

It is well known that the natural variations of the geomagnetic field induce electric currents inside the Earth which can be detected and measured at its surface as time-varying magnetic and electric fields. Since the lower the frequency of the electromagnetic signals the deeper the depth of investigation, by measuring those two fields over a wide range of frequencies it is possible to determine the subsurface electrical resistivity (or its reciprocal the electrical conductivity) distribution.

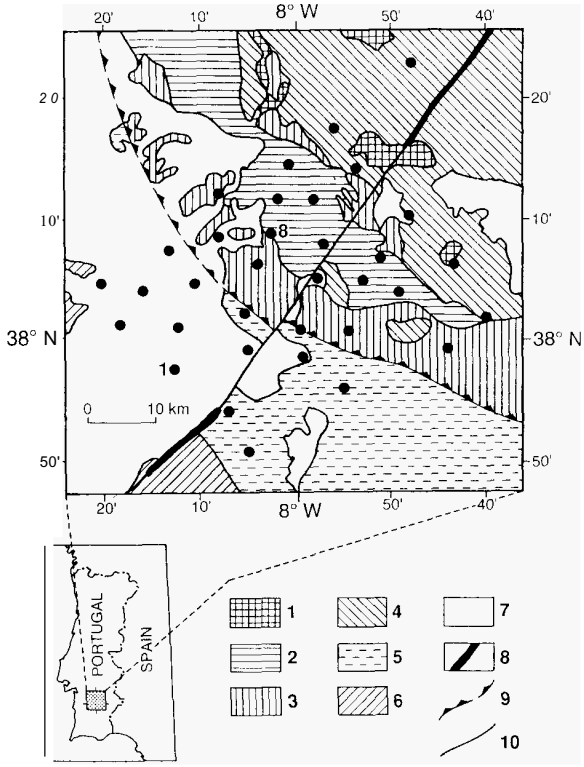


Figure 2. Geological sketch of the study area. The dots represent the MT sites. 1-granite; 2-porphyry; 3-gabbro-diorite complex; 4-undifferentiated Precambrian rocks; 5-undifferentiated Devonian rocks; 6-undifferentiated Carboniferous rocks; 7-Cenozoic terranes; 8-doleritic dyke associated with the Messejana fault; 9-Ferreira-Ficalho overthrust; 10-Messejana fault. (redrawn from the Geological Map of Portugal, Geological Survey of Portugal, 1968).

In a typical magnetotelluric survey three mutually orthogonal components of the magnetic field (two horizontal and one vertical) and two orthogonal horizontal components of the electric field are measured simultaneously at the surface of the Earth. Generally, the measurement directions are N-S and E-W and the magnetotelluric sites are chosen in such a way that they are far from any local sources of electromagnetic noise.

Processing of magnetotelluric data consists of calculating the impedance tensor, which, for each frequency, relates the measured magnetic and measured electric fields at a particular site. Several quantities may be obtained from the impedance tensor. Some of the most useful are the "skew", which gives an indication about the dimensionality of the geological structures being investigated, the "coherence", which measures the quality of the electromagnetic data, and the "angle of rotation", which indicates the strike of faults or other tectonic structures (Vozoff, 1991). The results of a magnetotelluric survey are generally displayed as electrical resistivity and phase curves as a function of frequency. However, since this is not the easiest way of visualizing the electrical resistivity (or electrical conductivity) distribution within the Earth, those curves are generally converted into electrical resistivity and phase curves as a function of depth by electromagnetic inversion procedures.

In southern Portugal the magnetotelluric survey was carried out using the University of Edinburgh Short Period Automatic Magnetotelluric system (SPAM MKIIb). The system records magnetic and electric signals in the range 128 - 0.031 Hz and allows automatic data acquisition and real time data analysis which enables in-field data control. More detailed information about the magnetotelluric survey may be found in Jones *et al.* (1992) and Correia *et al.* (1993).

The impedance tensor was used to calculate the determinant invariant of Berdichevsky and Dimitriev (1976) which is commonly used to make a first interpretation of magnetotelluric data. One assumption of the determinant invariant is that the geologic structures over which the magnetotelluric data were obtained are one-dimensional. Despite the fact that this assumption is not completely true for the study area in southern Portugal, it has been shown that, in most of the cases, it constitutes a good initial approximation to interpret two- and three-dimensional structures and to construct two- and three-dimensional electromagnetic models. After calculating the determinant invariant for each of the 34 magnetotelluric sites occupied during the field work, a hybrid Monte Carlo hedgehog inversion procedure was applied to them to convert the electric resistivity and phase curves as a function of frequency into electric resistivity and phase curves as a function of depth. The one-dimensional models so obtained were then used to construct electrical resistivity contour maps for several depths. Figures 3 and 4 show such maps for 500 m and 10,000 m depths.

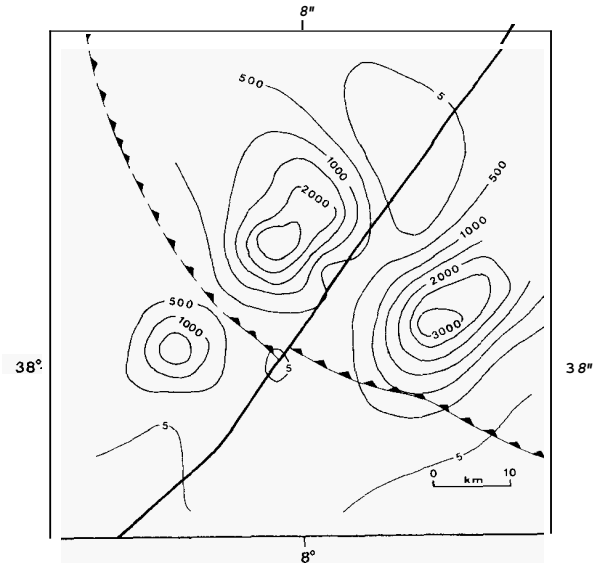


Figure 3. Electrical resistivity at 500 m depth in ohm-m (thin lines). Also shown are the Ferreira-Ficalho overthrust and the Messejana fault.

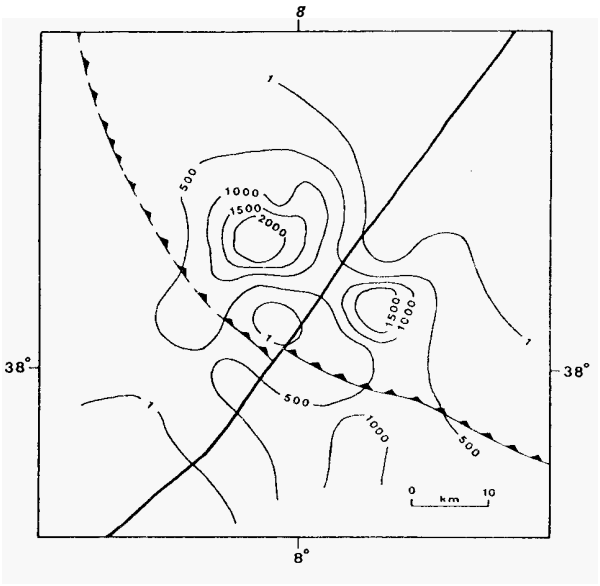


Figure 4. As Fig. 3, but for 10,000 m depth.

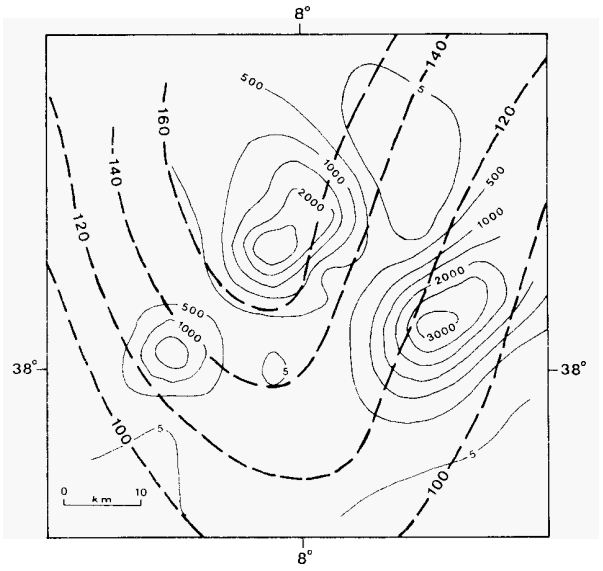


Figure 5. Heat flow density map superimposed on the electrical resistivity map at 500 metres. The heat flow density isolines (dashed lines) are in mW/m^2 and the electrical resistivity isolines (solid lines) are in ohm-m.

The main feature of these maps and others constructed for different depths, is the division of the area of the magnctotelluric survey into several deep-rooted high resistivity blocks separated by zones of low electrical resistivity which coincide with the trends of the two major faults that cross the area, i.e., the Messejana fault and the Ferreira-Ficalho overthrust.

DISCUSSION OF THE RESULTS

In Fig. 5 the HFD map shown in Fig. 1 is superimposed on tlic electrical resistivity map of Fig. 3 and it can be seen that a high electrical resistivity region (about 2,500 ohm-m at 500 m depth) coincides with the region where the HFD values are the highest. This coincidence was not expected because high HFD values generally correspond to low electrical resistivities (high electrical conductivities). To explain the high HFD values in the region of the MT survey two phenomena can he considered as a first approach: circulation of hot water and/or high heat production in the geologic foimations.

The MT results indicate two zones of low electrical resistivity that coincide with :he Messejana fault and the Ferreira-Ficalho overthrust. These zones may be interpreted as regions when: water flow may be taking place due to the higher porosity that is expected in and near the two faults. As a result, the water could transport heat from deep regions where temperature is higher to shallow regions and, therefore, enhance the HFD at the surface. A difficulty with this explanation is the lack of shallow hydrothermal manifestations in the region and in fact throughout most of southern Portugal.

To verify if heat production can explain the cause of the reported geothermal anomaly, geochemical analyses of some of the rock types that outcrop in the region of the anomaly were undertaken, The amounts of uranium, thorium and potassium were determined using gamma-ray spectroscopy and the heat production for the rocks analysed were calculated using Ryhach's method (Ryhach, 1976). The results of the heat production calculation are reported by Correia *et al.* (1993). For all the rock types considered (gabbros, quartz microdiorites, peralkaline microgranites and alkaline quartz diorites) the heat production values did not exceed 2.88 μW/m^3, a value that corresponds to normal values. This implies that the origin of the high HFD values cannot be explained in terms of heat production in the regional geologic formations.

A further attempt to understand the geothermal anomaly was undertaken hy constructing a set of geotherms for its central region. These were constructed hy considering a one-dimensional steady-state geothermal model with an exponential heat production distribution with depth (Lachenbruch, 1968):

$$T = T_o + \frac{q}{K} z + \frac{A_o D^2}{K} (1-e^{-z/D}) \quad (1)$$

where T is the temperature at depth z and T_o is the surface temperature, $q = Q - A_oD$ is the reduced heat flow (Roy *et al.*, 1968), Q is the surface HFD, K is the thermal conductivity, A, is the heat production at the surface and D characterizes the vertical distribution of heat sources. To construct the geotherms (shown in Fig. 6) the following parameters were chosen: since the highest HFD values are on or around the porphyry outcrop and laboratory analyses indicate heat production values of 2.88 μW/m^3 for that formation, the value of 3.0 μW/m^3 was assumed to represent the niaxiinuin heat production at the surface, A; T_o was assumed equal to 15° C; D was assumed to be 10 km (Cermak and Lastovickova, 1987) and from Haenel and Staroste (1988) q ($q = Q - A_oD$) was taken equal to 130 mW/m^2; K was assumed to be constant and equal to 2.6 W/mK (Chapman and Furlong, 1992; Cermak and Lastovickova, 1987). Curve (b) in Fig. 6 shows the calculated geotherm for a surface HFD of 160 mW/m^2. To compare with this geotherm, geotherms characterized hy the same parameters as above hut for surface HFD values of 200 mW/m^2 (curve (c)) (Duque and Mendes-Victor, 1993) and 90 mW/m^2 (curve (a)) (Almeida, pers. commun.. 1991; Almeida, 1990, 1993) are also shown.

The geotherms of Fig. 6 show that at a depth of 30 km, which in the study area corresponds to the average depth of the Moho (Caetano, 1983), the temperatures reach values of 1625' C, for the geotherm corresponding to a surface HFD value of 160 mW/m^2, 2086° C, for the geotherm corresponding to a surface HFD value of 200 mW/m^2 and 817° C, for the geotherm corresponding to 90 mW/m^2.

In the presence of free water, at depths near the bottom of the crust, intermediate to mafic rocks melt near 700° C to give a water-saturated melt of electrical resistivity of about 0.1 ohm-m (Wannamaker, 1986). On the other hand, in high-grade lower crustal rocks, where water is bound in hydrous minerals like amphibole and biotite, melting occurs at temperatures of about 850-

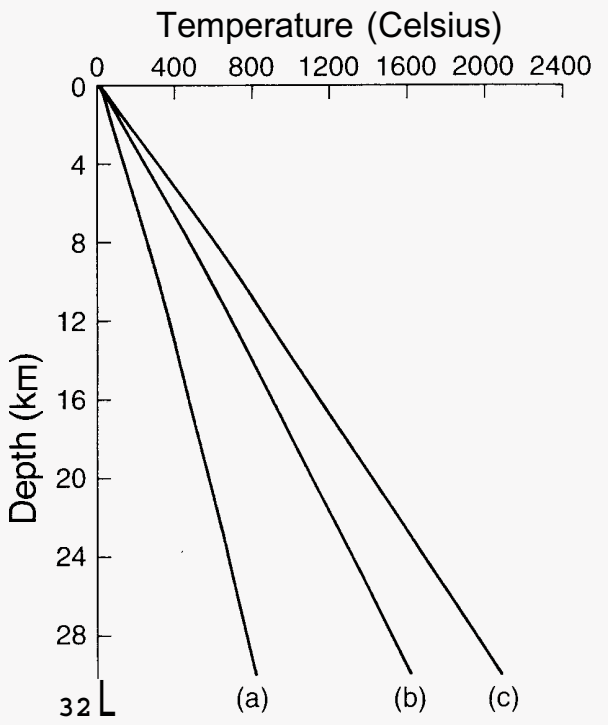


Figure 6. Calculated geotherms for surface HFD values of 90 (a), 160 (b) and 200 (c) mW/m^2. The values of the parameters used to perform the calculation are described in the text.

900° C in the absence of carbon dioxide and the melt has an electrical resistivity of abou: 1 ohm-m (Wannamaker, 1986). However, experimental work by Peterson and Newton (1989) indicates that carbon dioxide bearing lower crustal rocks with pyroxene or hydrous equivalents also melt at about 700° C. These results, together with the results from the MT survey which show that at depths of about 30 km the electrical resistivity below the area where the HFD values are the highest is about 1000 ohm-m lead to the conclusion that estimated HFD values in excess of 90 to 100 mW/m^2 are probably too high for the study region. Higher values than these would lead to partial melt, and the evidence clearly indicates that partial melt is not present in the lower crust below the region of the MT survey.

Heat flow density studies and geotherms constructed for other Hercynian regions in Europe show that surface HFD values range from 56 to 80 mW/m^2 and the temperatures at Moho depths range from 540 to 740° C (Cermak, 1982).

CONCLUSIONS

From the above discussion it is clear that an explanation for the high HFD values found in the region of the MT study is not apparent. Some conclusions may, however, be drawn from the MT survey. First, HFD values as high as 160 and 200 mW/m^2 do not reflect the thermal state of the crust in the region: in fact, the results of the MT survey are not compatible with such high HFD values or with experimental results or field results from other areas (Cermak and Lastovickova, 1987; Wannamaker, 1986). Furthermore, there is no geological or tectonic evidence for the existence of young magmatic activity (Ribeiro et al, 1979; Julivert et al, 1980). As a consequence, care should be taken when temperatures are to be extrapolated to deeper depths to infer the thermal regime of the crust in the region of the MT survey. Second, water flow from deeper geologic formations may explain the increase of the HFD values to those reported for the region; however, this interpretation presents some problems because of the lack of hydrothermal manifestations in the region.

Since heat production is normal for the rocks that outcrop in the area, it may be concluded that if the HFD values are properly calculated, then they reflect the presence of a surficial feature that cannot be the result of the thermal regime of the entire crust of the area. This is supported by the fact that the geothermal anomaly has high amplitude and short wavelength, which indicate that it is probably of shallow origin.

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REFERENCES

Almeida, C. (1990). Prospecção geotérmica: Determinação de gradientes geotérmicos em furos de sonda. *Boletim Informativo do INMG,* Lisboa. 120 pp.

Almeida, C. (1993). Prospecção geotérmica: Cálculo de condutividades térmicas em amostras rochosas. *Boletim Informativo do INMG,* Lisboa. 7 pp.

Berdichevsky, M.N. and Dmitriev, V.I. (1976). Basic principles of interpretation of magneto-telluric sounding curves. In: *Geoelectrical and Geothermal Studies,* KAPG Geophysical Monograph, Adam, A.(ed.), Academia Kiado, Budapest, Hungary, pp. 164-221.

Caetano, H. (1983). *Structure crustale de la zone Sud-Portugaise et de la zone Ossa-Morena d'après les études de sismologie experimentale*. Thèse 3e. cycle, University of Paris VI, Paris.

Cermak, V. (1982). Crustal temperature and mantle heat flow in Europe. *Tectonophysics,* 83, pp. 123-142.

Cermak, V. and Lastovickova, M. (1987). Temperature profiles in the Earth of importance to deep electrical conductivity models. *Pure and Applied Geophysics,* 125, pp. 255-284.

Chapman, D.S. and Furlong, K.P. (1992). Thermal state of the continental crust. In: *Continental Lower Crust,* Fountain, D.M, Arculus, R.J. and Kay, R.W. (eds.), Elsevier Scientific Publishing Company, pp. 179-199.

Correia, A., Jones, F.W., Dawes, G., and Hutton, V.R.S. (1993). A magnetotelluric deep crustal study in south-central Portugal. *Studia Geophysica et Geodaetica,* 37, pp. 331-344.

Correia, A., Duque, R., Maciel, C., Camelo, **S.,** Almeida, C., and Victor, L. (1982). Primeiras determinações do fluxo de calor em Portugal, *Boletim Informativo do INMG,* 56, pp. 3-13.

Duque, R. (1984). *Modelos te'rmicos da crusta terrestre e do manto superior*. Unpublished M.Sc. thesis, University of Evora (in Portugucsc).

Duquc, R. (1991). *Contribuição do fluxo de calor para a caracterização da litosfera nu região* do *Alentejo*. Unpublished Ph.D. thesis, University of Évora (in Portuguese).

Duque, R. and Mendes-Victor, L. (1993). Heat flow and deep temperature in South Portugal. *Studia Geophysica et Geodaetica,* 37, pp. 279-292.

Haenel, R. and Staroste, E. (1988). *Atlas of the Geothermal Resources in the European Community, Austria and Switzerland,* Commission of the European Communities. Verlag Th. Schaefer. Hannover, 74 pp, 110 plates.

Jones, F.W., Correia, A., Dawes, G.K., Hutton, V.R.S., Jones, P., and MacDonald, K. (1992). Preliminary results of a magneto-telluric survey over a geothermal anomaly in Portugal. *Physics of the Earth and Planetary Interiors,* 73, pp. 274-281.

Julivcrt, M., Martinez, F.J., and Ribeiro, A. (1980). The Iberian segment of the European Hercynian foldbelt. In: *Géologie de l'Europe*, Cogné, J. et Slansky, M. (eds.), Mémoire du B.R.G.M. no. 108, pp. 132-158.

Lachenbruch, A.H. (1968). Preliminary geothermal model of the Sierra Nevada. *Journal of Geophysical Research,* 73, pp. 6977-6989.

Peterson, J.W. and Newton, R.C. (1989). Carbon dioxide-enhanced melting of biotite-bearing rocks at deep-crustal pressure-temperature conditions. *Nature,* 340, pp. 378-380.

Ribciro, A., Antunes, M.T., Ferreira, M.P., Rocha, R.B., Soares, **A.** F., Zbyszewski, G., Moitinho de Almeida, F., de Carvalho, D., and Monteiro, J.H. (1979). *Introduction à la Géologie Générale du Portugal,* Serviços Geológicos de Portugal, Lisboa, Portugal, 144 pp.

Roy, R.F., Blackwell, D.D. and Birch, F. (1968). Heat generation of plutonic rocks and continental heat flow provinces. *Earth and Planetary Science Letters, 5,* pp. 1-12.

Rybach, L. (1976). Radioactive heat production in rocks and its relation to other petrophysical parameters. ***Pure and Applied Geophysics,*** 114, pp. 309-318.

Schermerhorn, L.J.G., Priem, H.N.A., Boelrijk, N.A.I.M., Hebeda, E.H., Verdumen, E.A.Th., and Verschure, R.H. (1978). Age and origin of the Messejana dolerite fault-dyke system (Portugal and Spain) in the light of the opening of the North Atlantic Ocean. ***Journal*** of ***Geology,*** 86, pp. 299-309.

Vozoff, K. (1991). The magnetotelluric method. In: ***Electromagnetic Methods in Applied Geophysics, Volume 2, Applications, Part B,*** Nabighian, M.N. (ed.), Investigations in Geophysics no. 3, SEG, Tulsa, Oklahoma.

Wannamaker, P.E. (1986). Electrical conductivity of water-undersaturated crustal melting. ***Journal*** of ***Geophysical Research,*** 91, pp. 6321-6327.