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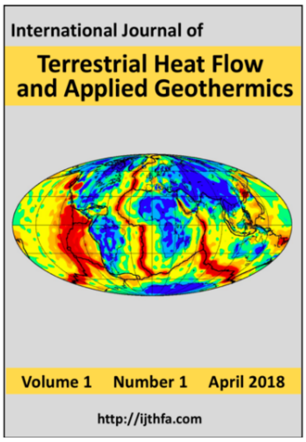

Heat Flow, Geotherms, Density and Lithosphere Thickness in SW of Iberia (South of Portugal)

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Abstract

Thermal structure, density distribution and lithosphere thickness in the SW part of the Iberian Peninsula are studied using data obtained in the South Portuguese Zone (SPZ) and SW border of the Ossa Morena Zone (OMZ) in the South of Portugal. Five different regions were defined, and models were built for each region. Geotherms were obtained using average density values from data published. The high values of heat flow density in these regions are attributed to occurrence of anomalous heat sources due to radioactivity content and exothermic chemical reactions associated to ore deposits in the zone. The results obtained with models based on isostasy in the region led to lithosphere thickness values between 95 and 96 km in the SPZ and a lower value of 94.5 km in the SW border of the OMZ. Analysis of geotherms shows lateral variations of temperature at the same depth. These lateral variations are compared with information obtained with seismic data.

1. Introduction

In the past, several models were presented trying to obtain lithosphere thickness and Moho depths in the Iberian Peninsula. All of them show a lithosphere anomaly in the SW of the Peninsula. The region studied in this work is located in the southwestern part of the Iberian Peninsula and covers the South Portuguese Zone (SPZ), with part of the Iberian Pyrite Belt, and the southern part of the Ossa Morena Zone (OMZ). This region is characterized by a strong positive Bouguer anomaly on the map of the Iberian Peninsula. The average altitude of the region is relatively low, and no mountains were considered in the models.

Fernandez, Marzán and Torne (2004) published a work presenting a model including the region of this study, based on data of altitude, geoid anomalies, gravity, heat flow and seismic profiles and velocity values. Some anomalies were obtained in the area indicating a lithosphere thickness less than 96 Km. Since then, several works have been published with similar results. All of them present anomalies associated to the lithosphere thickness of the region. Our work is restricted to a small part of the profiles used in previous works. It is a detailed study using models constructed with data from five different regions in the area. This is the last of a set of three works made by the author related with this subject. Since the presentation of the last work, new data were published, and a detailed analysis made. The models made for region 3 and 1 were altered and this led to new results. Models 2, 4 and 5 were inserted in the work, and a comparison of results was made. The model presented for region 1 does not include the Algarve Basin and the northern part of the region. Temperature variation in depth and in the horizontal direction at two different depths are presented and the results compared with seismic velocity variations found in the region.

2. Methodology

Physical properties obtained in the region of our study show heterogeneities. They justify the need to make five different models to study temperature and density distribution and to obtain information related to lithosphere thickness in the region. The data collected in the region are:

2.1 Heat flow data

Heat flow data were obtained in the region since 1982. We use in this work data published by Duque and Mendes-Victor (1993), Fernandez et al (1998) and Correia and Ramalho (2010). Figure 1 illustrates variation of heat flow density versus thermal conductivity and thermal gradient, obtained in the region. It is possible to see positive correlations of heat flow with thermal gradient and thermal conductivity. The high thermal conductivity values have been associated with ore deposits in the region. No explanation for the high thermal gradient values was reported in earlier studies. However, evidences for a relation between thermal gradient and gravity anomalies was presented (Duque and Mendes-Victor, 1993).

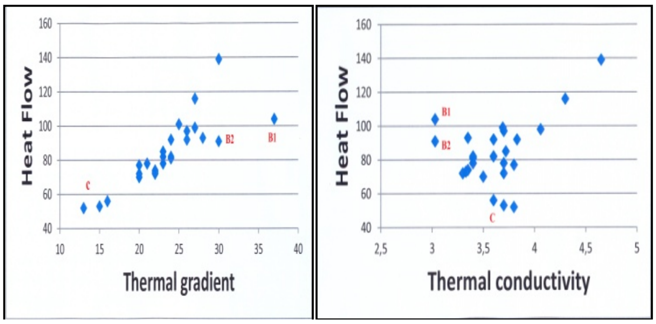

Figure 1 - Variation of heat flow with thermal gradient and thermal conductivity.

2.2 Seismic data

Crustal thickness distribution, was derived with seismic data (Dundar et al, 2016) in 5 different regions, identified as 1, 2, 3, 4 and 5. These are characterized by distinctly different values of heat flow, thermal conductivity and crustal depth values (Duque, 2016). A summary is presented in Table 1

Table 1 - *Parameter values used in the models for the five regions. HFD - heat flow density; TC - thermal conductivity; A_0 – Heat Production; H- altitude.*

Region	HFD (mW/m^2)	TC (W/mK)	A_0 ($\mu W/m^3$)	H (m)
1	77	3.5	2.2	150
2	82	3.5	2.3	130
3	100	3.7	5	210
4	78.5	3.65	3	250
5	74	3.35	2.4	200

Present crustal thickness values vary between 28 and 31 km, in the SPZ. Near the south border of the OMZ the thickness of the crust is nearly 32 Km. The same work also present V_P/V_S values for the region. A high value of 1.80 was found in the south-east part of the region where the minimum crustal thickness is 28 Km. The distribution of Moho depths is presented in the map of Figure 2.

2.3 Heat production in the crust

It has been difficult to obtain heat production values, especially for Region 3 (Iberian Pyrite Belt). In this region it is necessary to consider heat production by radioactive elements and also the heat generated in exothermic reactions occurring with water and pyrite (Beardsmore, 2016).

Measurements of gamma radiation were made in some parts of the SPZ and the contents of uranium, thorium and potassium obtained (Barberes et al, 2014). Heat production values were–obtained in the present work using appropriate density values for the region reported by Carvalho, Sousa, Matos and Pinto (2011) and Silva (2015). The concentrations of U, TH and K were presented in Barberes et al (2014).

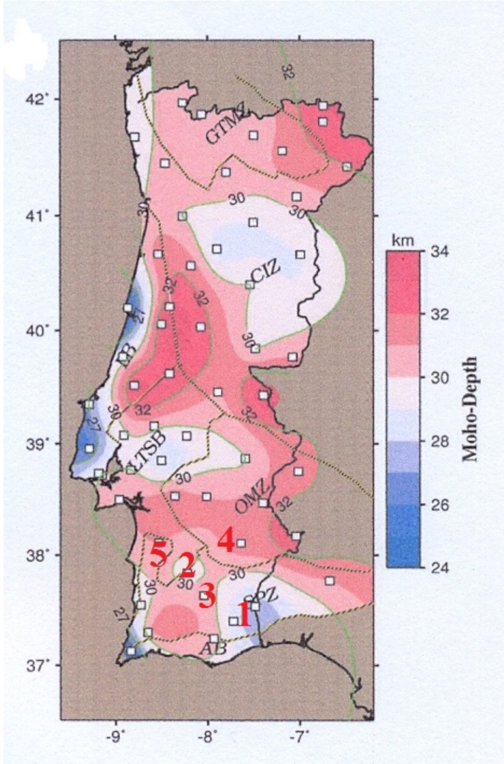

Figure 2 - Distribution of Moho depths in the study area. The dotted lines indicate boundaries of the regions.

2.4 Gravity data

Gravity data were obtained from the gravity maps of the Iberian Peninsula (Ayala et al, 2016; Torné et al, 2015). The maps show a gravity high located in the SW part of the Iberian Peninsula. This anomalous zone includes all the region on study in this work and also the Algarve Basin (onshore). No other region similar to this zone was found in the Iberian Peninsula. The reference density used in the mentioned work is 2670 Kg m^{-3}. Gravity anomalies of small wavelength were also considered in the region.

2.5 Geotherms

The depth temperature distribution is obtained by solving the steady-state heat conduction equation:

$$\frac{d}{dZ}\left[K(T)\frac{dT}{dZ}\right] + A = 0 \qquad (1)$$

where Z is the depth, T is temperature, $K(T)$ thermal conductivity and A the volumetric heat production. The upper boundary condition used is the temperature at the surface T(Z=0) of 15°C. The other boundary condition used is the heat flow density (q_0) at the surface, which is K(T)[dT/dZ].

2.6 Lithosphere models

A three-layer model composed of crust, lithospheric mantle and asthenosphere is considered. The elevation in the region is positive and the effect of the ocean water is not considered. The assumption of isostasy can be used to develop relations between elevation and density of the lithosphere and the asthenosphere. Using the work presented by Lachenbruch and Morgan (1990) it is possible to say that the elevation of the surface above sea level (E) is related with the thickness of the lithosphere (L) by

$$\mathbf{E} = \frac{\rho_a - \rho_L}{\rho_a}\mathbf{L} - \mathbf{L_0} \quad (2)$$

where ρ_a is the density of the asthenosphere, ρ_L is the density of the lithosphere and L_0 is the depth of the free asthenospheric level. Without any lithospheric load L_0 has a value of 2320 m. Equation (3) is obtained considering two layers (crust and lithospheric mantle) with constant density and applying isostasy:

$$(E+Z_c)\,\rho_c + (Z_L - Z_c)\,\rho_m = (E+Z_L)\,\rho_L \quad (3)$$

Combining equations (2) and (3)

$$(\rho_m - \rho_c)\,Z_c = \rho_a\,L_0 + E\,\rho_c + Z_L\,(\rho_m - \rho_a) \quad (4)$$

The geoid anomaly (N) is proportional to the dipole moment of the anomalous mass:

$$N = -\frac{2\pi G}{g}\int_{LC}^{Uc} Z\,\nabla\rho(Z)\,dZ + N_0 \quad (5)$$

where G is the universal gravity constant, g is gravitational acceleration at the Earth's surface and N_0, the integration constant. The value of N_0 is used to adjust the zero level of the geoid anomalies. Equation (6) is obtained solving the integral (5).

$$N = -\frac{\pi G}{g}\left[(Z_c^2 - E^2)\rho_c + (Z_L^2 - Z_c^2)\rho_m + (Z_{max}^2 - Z_L^2)\rho_a\right] + N_0 \quad (6)$$

It is assumed that the lithospheric mantle density ρ_m decreases linearly with temperature. The density of the mantle near the base of the crust was calculated using the relation:

$$\rho_m\,(Z) = \rho_a\,(1 + \alpha\,[T_a - T_m\,(Z)]) \quad (7)$$

ρ_a is density of the asthenosphere near the base of the lithosphere (3200 Kg m^{-3}), α the linear coefficient of thermal expansion (3.5 X 10^{-5} k^{-1}), T_a the temperature at the lithosphere-asthenosphere boundary - LAB (1350 ºC) and T_m *(Z)* the temperature at the depth Z in the lithosphere.

2.7 Models

Models were made for the five regions shown in Figure 2 using heat flow density and thermal conductivity values shown. These values are averages calculated on the basis of measurement data in the referred regions. The values of region 1 were calculated based on data from the southern part of the region, excluding the Algarve basin. A crust composed by three layers was considered. Thermal conductivity values for the middle and upper crust, excluding the upper layers is 2.5 W K^{-1}m^{-1}. The value used for the lower crust is 2.1 W K^{-1}m^{-1}. A value of 2.4 W K^{-1}m^{-1} was used for the intermediate crust in the OMZ (region 4) and in the region 1. The thermal conductivity of the mantle is assumed to vary with temperature. A radiative and a conductive contribution must be considered (Schatz and Simmons, 1972; Beck et al, 1978; McKenzie et al, 2005). No variation was considered for pressure effects. A heat production of 2 µWm^{-3} for the lower upper and middle crust and 0.1 µWm^{-3} for the lower crust were considered. For the upper layers of the crust the heat production value is given in Table 1. No heat production was considered in the mantle. The average values used for region 1 were obtained from measurements made in the Southern part of the region excluding the Algarve Basin, and the Moho depth considered is 29 Km.

The value of N_0 was obtained considering a reference column with a lithospheric depth of 129 Km and a crustal depth of 28 Km. The compensation level (Z_{max}) is 300 Km, the crustal density 2780 Kg m^{-3}, lithospheric mantle density 3245 Kg m^{-3} and the density of the asthenosphere 3200 Kg m^{-3}. A value of 2810 kg m^{-3} was assumed for the middle crust, a value of 2960 kg m^{-3} for the lower crust and a value of 6160 m was used for N_0.

Density values for the mantle near the Moho were calculated using equation (7) and the T_{Moho} values obtained in the model. A linear decrease with depth was considered and a mean value for the density of the mantle was used. Density values for the crust and the mantle are presented in Table 2.

Table 2 - Average density values obtained for lithosphere (ρ_L) lithospheric mantle (ρ_m) and crust (ρ_c) in Kg/m^3.

Region	ρ_L	ρ_c	ρ_m
1	3115.4	2836.2	3241.0
2	3118.8	2851.0	3239.6
3	3114.5	2854.9	3239.3
4	3113.1	2865.5	3239.9
5	3116.0	2868.4	3239.8

3. Results and discussion

Temperature values obtained for Moho depths are presented in Table 3. Values of heat flux from the mantle were obtained from the heat flow density values at the surface and the heat production values from sources in the crust. The value found for OMZ (region 4) is 35.2 mW m^{-2}. The values found in regions 2, 3 and 5 are in the interval 33.3 to 34.4 mW m^{-2}. The value found in region 1 is 35.1 mW m^{-2}.

Table 3 - *Values of temperature and depth at Moho, heat flow generated in the crust and geoid anomaly.*

Region	T_{Moho} (°C)	Z_{Moho} (m)	Q_c (mW/m^2)	N (m)
1	616.3	28896.7	41.9	8.4
2	635.0	29905.9	47.9	8.0
3	647.9	30863.4	66.7	8.5
4	638.4	31836.9	43.3	8.8
5	639.0	31866.7	39.6	8.5

The value of the thickness of the lithosphere obtained in the OMZ-region 4 (~94.5 km) is slightly inferior to those obtained for the SPZ, where the values vary between 95 and 96 Km. A value of 93.5 km was found in region 1.

The higher geoid anomaly value of 8.8 m found for OMZ was expected, and in agreement with values previously found by Corchete et al, 2005). The values obtained for SPZ region are slightly lower (between 8.0 and 8.5 m).

The density of mantle found is nearly the same in zones 2, 3, 4 and 5. The value obtained in zone 1 is slightly higher. High values of crust density are associated with regions where the temperature is lower (zone 5) and with ore extraction (zone 3). The value obtained in zone 4 (OMZ) is higher than obtained for the SPZ. The lowest value of the density of the crust was obtained for region 1, but it had the largest value for density of mantle. The lithosphere density for OMZ is lower than that obtained for SPZ. The effect of temperatures is visible in the density value for the lithosphere obtained in region 3.

The heat sources due to radioactive decay used in this work presents higher values than those used in the past. Two reasons can be presented for this fact. One of them is the high-density values found in the region and the other is the concentration values of radioactive isotopes. The material of the region suffered metamorphic reactions in the past and is possible to identify different formations suffering different types of metamorphism. Geologically speaking, the region cannot be classified as homogeneous. The heat content related with chemical reactions cannot be considered the same in all the region. This conclusion is taken based in the values of thermal gradient found and the relation, obtained in the past, between thermal gradient data and Bouguer gravity anomalies of small wavelength in the area (Duque and Mendes-Victor, 1993).

Some authors (Torné et al, 2015; Fernandez et al, 2004) use a constant value of thermal conductivity for the mantle. Calculations made with the value of 3.2 W $K^{-1}m^{-1}$ in our models made for SPZ led to an increase in lithosphere thickness ranging from 2 to 3.5 km. The introduction of T_a of 1330°C in our models led to a decrease of lithosphere thickness ~2 Km, a decrease in the mantle density values and an increase in the crust density. The values of N increase. The maximum difference between the N values found corresponds to about 5% of the value obtained.

Average crustal density values obtained in regions 2, 3, 4 and 5 are higher than the average value of 2840 $\pm$10 Kg m^{-3} presented in [17, 12]. The value found for region 1 is lower but located in the error range presented. The Bouguer anomaly map [19] and [12] shows a decrease of the anomaly from South to Northeast. Our lower value was found in region 4, located in the south border of the OMZ.

The temperature values found in the different geotherms show different values obtained at the same depth. The differences are more pronounced in the upper crust due to different values of conductivity in the upper layers and different values of heat sources near the surface. Results obtained at two different depths are shown at Table 4.

Table 4 - Temperature values obtained at 4 km and 12 km depths in the geotherms of the SPZ.

Depth	Region 1	Region 2	Region 3	Region 5
4	122.5	111.7	112.3	119
12	314.5	319.1	323.9	303.4

The values obtained in region 2 at 4 Km depth are lower than the values obtained in region 1. At 12 km depth the values obtained in regions 2 and 3 are higher than those obtained in regions 1 and 5. These results can be compared with seismic information (Salah, 2013; Salah et al, 2011). Using data obtained in Salah et al (2011) it is possible to see that seismic velocity of P and S waves at 4 Km depth in region 2 and region 3 are higher than the values obtained in regions 1 and 5. At 12 km depth the velocities obtained in region 2 and region 3 are lower than the values obtained in region 1 and region 5. High velocity values of seismic waves can be associated with low density values and / or regions with relatively high temperature values. The low values of temperature obtained in region 5 agree with data obtained in Attanayake et al (2017), showing a region with temperature values lower than values of the neighboring regions.

4. Conclusions

The results obtained show lithosphere thickness values between 95 and 96 km in SPZ. At the southern border of the OMZ the thickness of the lithosphere is relatively lower**.** The high values of the heat flux and its heterogeneity are due to different values of heat production in the crust. In addition to radioactive sources it is necessary to consider heat sources associated with exothermic chemical reactions in the crust. The values of the heat flow from the mantle vary between 33.3 and 35.1 mw m^{-2}.

The values obtained for mantle density are practically constant and the anomalies seems to be associated to different values of crust density.

The temperatures in the crust are relatively high compared to the expected values of heat flux obtained on continents. Lateral variations of temperatures were detected pointing to differences in thermal fields at different depths**.** These variations are in accordance with trends observed in distributions of seismic wave velocities obtained in the region.

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