Using Heat Flow Density Values Obtained in the Gulf of Cadiz and Gorringe Bank, Atlantic Ocean

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Abstract. The geothermal heat flow measured at the surface of the Earth is originated by different heat sources located at different depths of the planet. The main sources of heat flow in the crust are associated with radioactive decay of Uranium, Thorium and Potassium, in rocks. In some regions, additional heat sources must be considered such as exothermic chemical reactions. The value of the heat flow coming from deep regions, designated by “heat from the mantle”, must be obtained using indirect methods. In this work, the geoid height was used as indicator of alterations in “heat from the mantle” values, considering that the density decrease in regions with geoid height increase is related to high temperature values in the upper part of the mantle. The region on study is located in the Atlantic Ocean, SW of Cape St. Vincent and Cadiz Gulf. Temperature-depth values were obtained in twelve points of the region considering heat flow by conduction in the vertical direction, using published heat flow and thermal conductivity data. Layered models were made using data obtained in published seismic profiles. Moho depth values were used as lower boundary of the crust and mantle heat flow variations were made according geoid height increases. Ocean depth values between 2.5 and 4.3 km were used. A value of 5°C was used for temperature at the upper boundary (ocean bottom) of the models. Temperature calculus stops when a value of 1350 °C was attained. Lithosphere thickness is obtained considering this temperature value as temperature at the bottom of the lithosphere. Heat flow density values from 36 to 65.8 mW m² were used in the work with “heat from the mantle” values from 33 to 35 mw m². Curie Point Temperature (600°C) depths from 33 to 36 km were obtained. Lithosphere thickness values about 97 km were obtained in all the models.

1. Introduction

Data values used as the basis for this work were obtained in a region that has been the subject of several studies due to its geographical position, including parts of the edges and borders of the African and Eurasian plates, but also because historical data indicate that in the western part of the region, near the Gorringe Bank, earthquakes of high magnitude, sometimes accompanied by tsunamis which had caused destruction and loss of lives in Portugal, Morocco and some regions of Spain, had their source region. In present times, earthquakes originated in this region have been recorded [1]. The highest magnitude earthquake, M=8, occurred on the early morning of February 29, 1969. After this first event, a period of intense seismicity was felt in the region for several months. The eastern side of the region is characterized by a high thickness of sediments, associated with a negative gravity anomaly which is supposed to be originated by an accretionary prism of sediments delimited by a front of intense deformation (AWDF in Figure 1). The region is traversed by several faults.
Figure 1. Location of the source of some historical (rectangles) and registered (circles) earthquakes in the region studied (adapted from [1]). The stars show the location of temperature-depth profiles obtained in the present work. BG means Bank of Gorringe, PF means Horseshoe platform and MP is Marquês de Pombal fault. AWDF is the accretionary wedge deformation front (in red).

The heat flow density data used were obtained in December 2003 and published in 2009 [2]. The heat flow value obtained in the Gorringe Bank was published in 1989 [3]. As the geoid height data obtained with models EGM84, EGM96 and EGM2008 [4] give different values in almost the entire region, the year in which the measurements were made may be important in the analysis of the results obtained. The region of the Gorringe Bank where the heat flow density value was obtained is a region where the geoid height value has remained practically constant in the three years mentioned.

2. Data used
The heat flow density values, ocean depth values and thermal conductivity values of the first layers were obtained from the analysis of the values published in [2]. The values used in point DG were published in [3] and are incorporated into the “World Heat Flow Data Base” of the International Heat Flow Commission. Geoid height values obtained with models GEM1984, GEM1996 and GEM2008 are available online for the region [4].

2.1. Heat flow density values in the region
Seven heat flow density values were considered in the Gulf of Cadiz region, four heat flow density values are close this region but located in the western and southern borders respectively. Two values were measured near the Marquês de Pombal Fault and one value in the Gorringe Bank (see Figure 1). Points A, B, D and E are located on Jurassic Oceanic crust belonging to the Central Atlantic. Points C, F, G, H, I, J and K are located in Jurassic Oceanic crust belonging to the Western Thetys, Point L is located in Thinned continental crust (slope domain) and points M and DG are located on Lower Cretaceous exhumed mantle [5].

Points F and C are located near the border of the two types of oceanic crust and in the borders of SWIM lineaments with lateral slip movements [6]. The values A, B and C are located near the southern border of the wedge deformation front close to the Moroccan coast. They are located over seismic profile SISMAR 16 [7]. The lowest value (33 mW m$^{-2}$) of heat flow from the mantle was used in values A and B. The values D, E, F and G were obtained at the same latitude in a profile from West to East traversing the western border of the Gulf of Cadis sedimentary prism (see figure 1). The values H, J, K and I were obtained at latitude values close to 36° N near the border of the sedimentary prism
close to the “Accretionary wedge deformation front” (see Figure 1). The values L and M includes heat flow density measurements obtained near Marquês de Pombal Fault at latitude values close to 37° N. The last value, DG, includes one heat flow density measurement obtained in the Gorringe Bank.

Heat flow density values between 36 mW m\(^{-2}\) (point G) and 65.8 mW m\(^{-2}\) (point M) were used. Thermal conductivity values between 1.09 W K\(^{-1}\)m\(^{-1}\) (points F, G and DG) and 1.26 W K\(^{-1}\)m\(^{-1}\) (point J) were used for the first layer (below the bottom of the ocean). Ocean bottom depths from 2 Km (point C) to 4.3 km (points I and H) were used [2][3].

2.2 Geoid height values in the region

The global map of geoid anomaly obtained with Model EGM2008 [10] [11] shows that the region on study is located in a strong positive geoid anomaly (>40 m) clearly visible using the spherical harmonic degrees from 2 to 360. Geoid height values increase with latitude values but presents variations with longitude values. In the Gorringe Bank, located in the western part of the region studied, a positive geoid anomaly exists overlapping the anomaly already mentioned. Due to the year of the heat flow density measurements (2003) the values used in the present work are average values obtained with GEM2008 and GEM1996 models [4].

3. Methodology

The heat flow measured at the surface of the Earth is originated by different types of heat sources located at different depths. In the present work it is considered that heat flow by conduction in the vertical direction crosses the lithosphere in a stationary regime. The temperature- depth distribution is obtained by solving the steady-state heat conduction equation:

\[
\frac{d}{dz} \left[ K(T) \frac{dT}{dz} \right] + A = 0 \quad (1)
\]

The temperature at the higher boundary of the models (bottom of the ocean) is considered the same in all the region (5°C). In the lower boundary (lower limit of the lithosphere) the temperature values used is 1350°C. The models used are formed by horizontal layers of different thickness where constant values of thermal conductivity and heat production are considered.

In the superior layer (located just below the seabed) thermal conductivity values used were measured during the works of heat flow density measurement and heat production due to decay of radioactive elements uranium, thorium and potassium was considered as 0.5 μW m\(^{-3}\). The number of layers and thickness used were deduced from seismic models built and published about the region [5][7][10][11][12][13].

Values of 0.1-0.2 μW m\(^{-3}\) were used as heat production in the lower layers of the crust, with thermal conductivity values of 2 W K\(^{-1}\) m\(^{-1}\). No heat sources were considered in the upper layers of the upper mantle but thermal conductivity values depend on temperature, with a value 3.6 W K\(^{-1}\) m\(^{-1}\) in the deepest layer considered.

Values from 33 to 35 mW m\(^{-2}\) were used as heat flow density from the mantle taking into account geoid height values for the region [4]( the relation used was made considering that the increase in geoid height is related with a density decrease that occurs due to high temperature values in the mantle)[14][15]. The highest values of heat flow from the mantle were used in regions with highest geoid height values. The value 1350°C was used for temperature of the deeper boundary of the lithosphere.

The number of layers and thickness used were deduced from seismic models built and published about the region [5][7][10][11][12][13].

Lithosphere thickness values were obtained considering the depth where this temperature value was obtained and the depth value of the ocean floor.
The temperature value of 600°C was used as “Curie Point Temperature” of the rocks in the region.

3.1 Temperature-depth profiles

Surface heat flow density values ($Q_o$), heat flow values generated in the crust ($Q_C$), heat flow from the mantle values ($Q_m$) and Geoid height values used in the profiles considered are presented in Table 1. The ratio $Q_C/Q_o$ obtained from the values presented (excluding point G) is located between 0.29 and 0.47 with the highest values located in the western part of the region shown in figure 1 (points D, J and K are located close to the accretionary wedge deformation front and point M is located in the western side of Marquês de Pombal fault).

Table 1. Details about Heat Flow Density values used in the temperature depth profiles

| Profile | $Q_o$ (mW m$^{-2}$) | $Q_C$ (mW m$^{-2}$) | $Q_m$ (mW m$^{-2}$) | Geoid Height (m) |
|---------|---------------------|---------------------|---------------------|------------------|
| A       | 48                  | 15                  | 33                  | 39.9             |
| B       | 50                  | 17                  | 33                  | 40.3             |
| C       | 53                  | 20                  | 34                  | 40.8             |
| D       | 57                  | 23                  | 34                  | 43.6             |
| E       | 50                  | 17                  | 34                  | 43.2             |
| F       | 48                  | 14                  | 34                  | 42.9             |
| G       | 36                  | 2                   | 34                  | 42.6             |
| H       | 55                  | 21                  | 34                  | 43.8             |
| I       | 53                  | 19                  | 34                  | 43.7             |
| J       | 58                  | 24                  | 34                  | 43.7             |
| K       | 58                  | 24                  | 34                  | 43.7             |
| L       | 49                  | 14                  | 35                  | 54.6             |
| M       | 66                  | 31                  | 35                  | 56.9             |
| DG      | 49                  | 15                  | 34                  | 50.4             |

Heat flow density values from the mantle are 34 mW m$^{-2}$ in all the region studied except near Marquês de Pombal fault (35 mW m$^{-2}$) and in values located at lower latitudes (33 mW m$^{-2}$) near Moroccan coast, points A and B. Point G with the lowest heat flow density value and a geoid height close to the values obtained in D, E and F, was considered an anomalous point with a deficit of heat sources in the crust. For this reason the ratio $Q_C/Q_o$ in this model is only 7%. The $Q_C/Q_o$ ratio value varies between 30% and 47% on the other models. A special attention was given to the value obtained in the Gorringe Bank (DG point). The upper layer found in this region is formed by sediments with thermal conductivity values identical to those found in F and G points located in the Gulf of Cadiz but the Gorringe Bank is formed by rocks from the mantle like serpentinites and Gabbros. The heat production due to radioactive decay is low in this rocks and the serpentinization of peridotites reacting with seawater is an exothermic reaction. The heat production values used in this region must be seen as the two heat sources mentioned. The ratio between the heat generated in the crust and the heat measured at the surface in this point was 30%. A value of 47% was obtained in point M near the Marquês de Pombal fault in the Northern part of the Gorringe Bank and a value of 40% was obtained in point D located to the east of point DG, near the deformation border of the Gulf of Cadiz.

Table 2 shows some results obtained from temperature-depth profiles made for each heat flow density value location. Ocean bottom depths used, temperature values obtained at 20 and 50 km depth, Curie Point Temperature depths (temperature values of 600°C were considered) and lithosphere thickness obtained (difference between depth of 1350 °C and ocean bottom depth) can be seen on this Table.
### Table 2. Information related with temperature-depth vertical profiles

| Profile | Ocean bottom (km) | T20 km (°C) | T50 km (°C) | CTD (km) | L (km) |
|---------|-------------------|-------------|-------------|---------|--------|
| A       | 4                 | 376         | 781         | 36      | 96     |
| B       | 3                 | 415         | 807         | 34      | 96     |
| C       | 2.5               | 429         | 811         | 33      | 97     |
| D       | 4.2               | 394         | 782         | 36      | 97     |
| E       | 3.7               | 391         | 781         | 36      | 97     |
| F       | 3.2               | 404         | 792         | 35      | 97     |
| G       | 2.7               | 407         | 794         | 35      | 97     |
| H       | 4.3               | 392         | 781         | 36      | 97     |
| I       | 4.3               | 383         | 775         | 36      | 97     |
| J       | 4.2               | 398         | 780         | 36      | 97     |
| K       | 4.2               | 398         | 780         | 36      | 97     |
| L       | 2.6               | 402         | 793         | 35      | 97     |
| M       | 3.9               | 381         | 777         | 36      | 97     |
| DG      | 3.5               | 384         | 780         | 36      | 97     |

Point C presents the highest values of temperature obtained at 20 and at 50 km depth. The ocean bottom depth in this point is the lowest value used in the present work. The difference between the highest and the minimum temperature value at 20 km depth is 53 °C and the value obtained at 50 km depth is 36 °C. The lowest temperature value at 20 km was obtained in point A (376°C). At points A, D, E, H, J and K, located near the accretionary wedge deformation front, temperature values obtained at 50 km depth show similar values close to 780°C. In points located further away the deformation front (points B, C, F and G located near SWIM lineaments [5]) temperature values at 50 km depth are higher. Curie temperature depths found (33 to 35 km) are also lower than values found near the deformation front (36 km). Due to differences in water bottom depths, temperature values obtained at 20 km depth do not shows the similarities found at 50 km depth.

#### 3.2 Models and results

Table 3 shows the first layers of the models made in points A and J, located in the Gulf of Cadiz region, near the deformation front, in Jurassic Atlantic crust (point A) and Jurassic Western Thetys crust (point J)[4]. Ocean bottom depths presents similar values in both models but the heat flow density in point A is 47.7 mW m⁻² and 57.9 mW m⁻² in point J. Point A is located at latitude 34.77°N with a geoid height of 39.9 m and point J at latitude of 35.89°N and geoid height of 43.7 m. The ratio Qc/Qo in point A is 0.31 and in point J 0.42. This differences in heat production in the crust and heat flow at the surface are related with differences in temperature values at depths until 45 km. For higher depths, temperature values obtained at the same depth are identical in both profiles.

### Table 3. First layers in model A and model J

| Depth (Km) | Thermal conductivity K (W k⁻¹ m⁻¹) | Heat production A (µW m⁻³) | Depth (Km) | Thermal conductivity K (W k⁻¹ m⁻¹) | Heat production A (µW m⁻³) |
|------------|-----------------------------------|-----------------------------|------------|-----------------------------------|-----------------------------|
| 4-6        | 1.10                              | 0.5                         | 4.2-5      | 1.26                              | 0.5                         |
| 6-8        | 1.15                              | 1.5                         | 5-11       | 1.4                               | 2.4                         |
| 8-9        | 2.10                              | 2.0                         | 11-15.5    | 2.5                               | 2                           |
| 9-11       | 2.20                              | 2.0                         | 15.5-18.5  | 2.0                               | 0.2                         |
| 11-13      | 2.30                              | 2.0                         | 13-19      | 1.90                              | 0.2-0.1                     |
Points E and F are located at the same latitude but point E is closer to the deformation front than point F. Ocean bottom depth is 3.7 km in point E and 3.2 km in point F. The heat flow density values are 50 mW m$^{-2}$ in point E and 48 mW m$^{-2}$ in point F. Geoid height values are similar and $Q_m$ value used is the same in both models. The ratio $Q_c/Q_o$ in point E is 0.34 and in point F is 0.30. Temperature values obtained with model E are lower than temperature values obtained with model F at the same depth. The difference obtained at 10 km depth is 14°C. This value decreases with higher depth values.

Points D and H are located at latitude values of 35.49°N and 35.94°N respectively. Both values are located close the deformation front but on the western side of it. Ocean bottom depth is 4.2 km in D and 4.3 km in H. The heat flow density values are 57 mW m$^{-2}$ in point D and 55 mW m$^{-2}$ in point H. Geoid height values are similar and $Q_m$ value used is the same in both models. The ratio $Q_c/Q_o$ in point D is 0.40 and in point H is 0.39. Temperature values are similar in both models at depth values higher than 10 km.

The Marquês de Pombal fault separates two different regions. On the eastern side of the fault thinned continental crust forming the slope domain [5] presents low heat flow density values and low bottom depth values (point L). On the western side deepest bottom values were measured (lower than 4 km) and highest heat flow density values were obtained (point M). Geoid height values used are 54.6 m in the eastern side and 56.9 m in the western side of the fault. Point M has the highest heat flow density value used in this work (65.8 mW m$^{-2}$). The $Q_c/Q_o$ value in point L is similar to the value found in point F but the value obtained in model M is the highest value found in this work (0.47).

Point M is located near the Gorringe Bank and the heat sources in the region can be related with chemical reactions occurring in that region. Curie temperature depth values of 35 km were obtained in L, F and G points and 36 km were obtained in points M and DG.

4. Discussion and conclusions

No heat flow density measurements are shown in the source region of the earthquakes of high magnitude (see Figure 1). Due to the proximity of the Bank of Gorringe and its heat sources, this region must receive heat flowing in the horizontal direction increasing the heat flow in the vertical direction. As the heat flow from the mantle used in the work is related with geoid height in the region it is expected a decrease in this value due to the decrease in geoid height observed at longitude values from -10 to -11° W (see Figure 2) [4].

The main differences in heat flow density values in the region were explained by heterogeneities in the crust. A heat from the mantle value of 34 mW m$^{-2}$ was used in the Gulf of Cadis region and in the Gorringe Bank. A value of 35 mW m$^{-2}$ was used near the Marquês de Pombal fault located at high latitude values. Temperature values around 780 °C were obtained at 50 km depth except in points located near some faults (points B, C, F and G in the southern part of the region and point L near the Marquês de Pombal fault). Lithosphere thickness values around 97 Km and Curie temperature depth values of 35-36 km were obtained in this work. This values are similar with values obtained in other works [14] and [15].

![Figure 2. Geoid height values at latitude 36.0 N obtained with model EGM96 [4].](image-url)
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