Heat Flow in SW of Galicia And NW of Portugal. The Interpretation of a Seismic Anomaly

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Abstract. Four heat flow density values and five temperature-depth profiles were obtained in a heterogeneous region considering heat flow by conduction in the vertical direction, and heat sources in the crust due to radioactivity decay. The heat produced in the upper layers of the crust was obtained based on gamma-ray charts and published data of laboratory radioactivity measurements on samples taken from the region. Seismic data were used to obtain the thickness of the different layers of the upper and middle crust and the depth of the Moho discontinuity considered coincident with the crust/mantle boundary. The heat flow at the surface is obtained by adding the heat flow from the mantle with the heat generated by the radioactive sources in the crust. The method was applied to a region with one measured heat flow density value (Ourense) and four points without any heat flow density measurement. A heat flow value from the mantle was obtained with Ourense data. Special attention was given to a region (A) with a seismic anomaly near the surface. The anomaly was explained by mass deficit near the surface that gives rise to an abnormal density value and an increase in seismic wave velocity values. The decrease in density is due to the presence of water in the region forming an aquifer. Geothermometer values obtained from samples of water in the thermal springs of Tuy (Spain) and Monção (Portugal) were used as the water temperature at the bottom of the aquifer. Isostatic balance in the region was considered to obtain density values and the amount of water in the region. Thermal conductivity and radioactivity heat source values in the region were obtained considering the amount of water in the region. Values from 86 to 97 mW/m² were obtained using the same value of heat flow from the mantle. This is due to different values of heat produced in the crust due to different thickness layer values or/and to different heat production values.

1. Introduction
The principal aim of this work is to obtain information about heat flow density and temperature-depth values in a region without measured heat flow density values using different types of geophysical data obtained in the region for other purposes and available from the literature. Special attention is given to a region with seismic velocity anomalies explained as mass deficit due to an aquifer with hot water in the region.
2. The region on study
The region of this study is located in Northwestern Portugal and Southwestern Galicia (Spain) in the Western part of the Iberian Peninsula between latitudes 41.55 °N and 42.7 °N and longitudes 7.9 °W and 8.7 °W. One measured heat flow density value was reported [1] for this region.

The main type of geological formations in the region is granitic rocks. Three different ages of granites with different contents of Uranium Thorium and Potassium were identified in the region [2][3] in formations with different thicknesses [4]. These results can be complemented by radiometric charts [5] presenting high values of exposure rates in the region. The region is traversed by several faults and two hot springs are identified near latitude 42.2 (Model-A).

The heterogeneity of the region is shown on seismic models of the crust [4] (vertical profiles and horizontal distributions at several depths) and in gravity data [6] [7]. Vertical profiles F-F’ and A-A’ traverses the region and were used in the present work. Different Moho depth values were identified in the region [8] [9]. Geoid height values over 56.0 m were obtained [10] in the region except in E where a value of 55.85 m was found.

3. Methodology
The method used is based on the assumption that the heat flow measured at the surface \( Q_o \) in a region without important tectonic thermal events includes the contribution of deep heat sources located in the mantle and heat sources located in the crust \( Q_c \). Assuming a heat flow value from the mantle and knowing the value of the heat sources in the crust it is possible to find the heat flow at the surface. Five models were made in the region using crustal thickness values obtained on seismic profiles and heat production of 0.1 µW m\(^{-3}\) in the lower crust and 2.0 µW m\(^{-3}\) in the intermediate crust. No heat sources are considered in the upper mantle. The heat production by the decay of radioactive elements in the upper layer of the crust was obtained from radioactivity charts and the heat sources due to granites [11] and previously published for the region. Geotherms were obtained using the heat flow density values found and considering steady-state heat conduction in the vertical direction [12]. Thermal conductivity values of 2.1 W m\(^{-1}\)K\(^{-1}\) and 2.5 W m\(^{-1}\)K\(^{-1}\) were used for the lower and upper crust respectively. For the upper layers of the crust, thermal conductivity values measured in samples obtained in mainland Portugal and Ourense [1] were used. A value of 15° C was used as temperature values in the upper boundary of the model. The heat flow from the mantle was obtained in Model -C using the heat flow density value measured in Ourense [1].

In Model-A made for a region with high-velocity seismic values in the upper layer of the crust and an ascent in Moho level and lower/intermediate crust boundary a low-density value was used considering that the mass deficit near the surface is compensated by the high-density values in the lowest layers of the model. Temperature values obtained with geothermometers (Monção and Tuy thermal springs are relatively close) were used for the temperature at the bottom of the aquifer. Thermal conductivity values were obtained considering a thermal conductivity value of 0.6 W K\(^{-1}\)m\(^{-1}\) for water. A zero heat production by water was considered in the aquifer region.

4. Models and results
Five models were built to obtain the heat flow density and temperature-depth profiles in the region using the method described. The profile F-F’[4] in three different latitude values was used for three models and the profile A-A’, longitude 8.0 °W, was used for the fourth model. No vertical profile traverses the region of Model C- Ourense (latitude 42.34 N and longitude 8.03 W). This model was built using horizontal distributions of velocity values obtained at different depths [4].
4.1 Model C - Ourense
A measured heat flow density value of 95 mW m\(^{-2}\) was known in the region [1]. The thickness, thermal conductivity, and heat production values due to radioactive decay in the different layers are shown in Table 1. Using the model presented a heat flow value of 35.1 mW m\(^{-2}\) from the mantle to the base of the crust was found. This value was used as a reference to obtain the heat flow values at the surface with the other models.

| Depth (Km) | Thermal conductivity K (W k\(^{-1}\)m\(^{-1}\)) | Heat production by radioactive elements A (µW m\(^{-3}\)) |
|------------|---------------------------------|---------------------------------------------|
| 0-7        | 3.27                            | 4.5                                         |
| 7-18       | 2.50                            | 2.0                                         |
| 18-21      | 2.4                             | 1.9                                         |
| 21-28      | 2.1                             | 0.1                                         |

4.2 Model B and Model E
These models are located in profile F-F´[4] at latitudes 41.6 °N (Model E) and 42.6 °N (Model B), (Table 2). The main differences between models B and E are the surface altitude (462 m in B and 59 m in E) and Geoid height (56.3104 m in B and 55.8539 m in E). They can give us the heat flow density in the region without the anomaly related to the aquifer (Model-A).

| 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\(^{-3}\)) |
|------------|---------------------------------|---------------------------------|------------|---------------------------------|---------------------------------|
| 0-4        | 3.2                             | 4.5                             | 0-5        | 3.2                             | 4.0                             |
| 4-19       | 2.5                             | 2.0                             | 5-18       | 2.5                             | 2.0                             |
| 19-22      | 2.3                             | 1.3                             | 18-21      | 2.3                             | 1.2                             |
| 22-27      | 2.1                             | 0.1                             | 21-30      | 2.1                             | 0.1                             |

4.3 Model D
The profile A-A´ [4] was used to make this model at longitude 8.0 °W. The heat production due to radioactivity in the upper layer of the crust has the maximum value used and the heat originated in the crust is also high. Moho depth used presents also the highest value used in this work. The transition intermediate/lower crust is located at 19 km depth (Table 3).

| Depth (Km) | Thermal conductivity K (W k\(^{-1}\)m\(^{-1}\)) | Heat production A (µW m\(^{-3}\)) |
|------------|---------------------------------|---------------------------------|
| 0-8        | 3.27                            | 5.0                             |
| 8-13       | 2.5                             | 2.0                             |
| 13-19      | 2.3                             | 1.3                             |
| 19-30      | 2.1                             | 0.1                             |

4.4 Model A
This model is located in profile F-F´[4] at latitude 42.2°N. The region is characterized by a yellow color (high velocity value) ascending to the surface. At 6 km depth, it is possible to identify a small and narrow green spot interpreted in the present work as being an impermeable layer, with zero porosity, forming the bottom of an aquifer in the region. A mass balance in the region was made considering that the mass deficit verified near the surface due to the existence of the aquifer is compensated by the rise of 2 km of the mantle and lower crust with higher densities. A temperature
value of 160 °C was considered as water temperature at 6 km depth (value obtained with geothermometers in Galicia). Thermal conductivity values of 3.3 W K⁻¹ m⁻¹ and 0.6 W K⁻¹ m⁻¹ were used for the conductivity of the rock without water and for water respectively. No heat production is associated with water in the region. Thermal conductivity and heat sources were calculated for each layer taking into account porosity values. The results obtained are shown in Table 4.

**Table 4. Model A**

| Depth (Km) | Thermal conductivity K (W k⁻¹m⁻¹) | Heat production by radioactive elements A (µW m⁻³) |
|------------|-----------------------------------|-----------------------------------------------|
| 0-2        | 2.76                              | 3.6                                          |
| 2-4        | 3.0                               | 4                                            |
| 4-6        | 3.17                              | 4.3                                          |
| 6-7        | 3.3                               | 4.5                                          |
| 7-10       | 2.5                               | 2                                            |
| 10-14      | 2.4                               | 2                                            |
| 14-20      | 2.3                               | 1.25                                         |
| 20-28      | 2.1                               | 0.1                                          |

Data related to heat flow density values and heat production in the crust are shown in Table 5. Model D presents highest values found in the work but the influence of layer thickness is visible in models A, B and C that with the same value of heat production at the surface ($A_o$) have different values of heat flow at the surface and heat originated in the crust ($Q_c$). The presence of the aquifer in Model A originates a decrease in heat flow due to a decrease in heat production in layers with water and a decrease in thermal conductivity. $Q_c$ values are similar in model E and model A but they are associated with very different backgrounds. $Q_c/Q_o$ values obtained in the present work belongs to the range obtained in similar regions [13] in Portugal.

**Table 5. Heat flow density and heat production values near the surface**

| Model | $Q_o$ (mW m⁻²) | $Q_c/Q_o$ | $A_o$ (µW m⁻³) |
|-------|----------------|-----------|----------------|
| A     | 85.7           | 0.59      | 4.5            |
| B     | 89.5           | 0.61      | 4.5            |
| C     | 95             | 0.63      | 4.5            |
| D     | 96.5           | 0.64      | 5              |
| E     | 85.5           | 0.59      | 4              |

Some information obtained from temperature-depth results is presented in Table 6. CPD is the depth of a temperature of 570 °C (considered as the average value for Curie Point Temperature of magnetic minerals in the crust) is found and LT is the depth of 1350°C, considered as the possible temperature of the base of the lithosphere, not related with seismic results. Equal values of CPD and LT were found in other regions of Portugal [13].

**Table 6. Surface altitude values and information from geotherms**

| Model | Altitude (m) | CPD (km) | LT (km) | CT (km) |
|-------|--------------|----------|---------|---------|
| A     | 100          | 28       | 96      | 28      |
| B     | 462          | 27       | 96      | 27      |
| C     | 385          | 27       | 96      | 28      |
| D     | 526          | 28       | 96      | 30      |
| E     | 59           | 28       | 96      | 30      |
Figure 1 shows a linear relationship between the heat flow density value at the surface and geoid height in the same place. This relationship is not verified with the results of model A due possibly to the mass deficit in the region associated with the presence of water and a decrease in the heat flow value. A similar relationship was found in the Beiras region located SE of this region near the border with Spain [13].

![Figure 1. The relationship between geoid height and heat flow in the region](image)

5. Conclusions
It is possible to obtain heat flow density values in regions not affected by ascending waters, with the method presented. The differences in heat flow values at the surface are mainly due to heat sources in the crust and thickness of their layers. A velocity seismic anomaly “yellow zone” and the heat flow density value obtained in this zone may be explained by a low-density value (mass deficit) and lower heat production in the crust due to the existence of water in the region. The heat flow density in the anomalous region is different from the value obtained in other works [14] [15] but different types of data obtained in the region were used in the present work. The heat flow values obtained agree with values found in the Beiras region and the southern part of Portugal.

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