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Update Heat Flow Density Map for Portugal

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ABSTRACT

New thermal conductivity, heat production and temperature data obtained in Portugal were used to produce a new heat flow density map. Heat flow density values in Portugal vary between 42 and 115 mW/m^2 and allow the extrapolation of temperatures to depths not yet reached by existing boreholes. Additionally, temperature maps at 500 and 1000 m depths and a two-dimensional model constructed along a north-south profile in the area where there is more geothermal information are given.

1. INTRODUCTION

In recent years, geothermal studies have gained intensity due to heightened climate awareness and the need to diversify energy sources. Portugal is no exception to this trend. An update heat flow density map, a geothermal gradient map, temperature maps at 500 and 1000 m, and a two-dimensional model of southern Portugal are presented in this paper. The data used to construct the maps consist of temperature logs obtained in several boreholes in mainland Portugal, thermal conductivity measurements performed in rock samples or cores from selected boreholes, and heat production values. Temperature logs from about 90 boreholes were compiled to estimate heat flow density values. These boreholes include mining wells, water wells, and oil prospecting wells. The entire set of temperature logs and thermal properties of rocks or cores was analyzed for consistency and reliability, and only data that fulfilled the selection criteria described later were accepted to be processed and used to draw the maps.

Some of the data presented here were collected by the authors, and some were presented in other works (e.g., Correia *et al.* (1982), Camelo (1987,a,b), Haenel *et al.* (1988), Almeida (1992), Duque (1991), Duque and Mendes-Victor (1993), Correia and Jones (1997), Correia and Ramalho (1998), Fernandez *et al.* (1998), Correia and Ramalho (1999), Correia and Safanda, (2002), Correia *et al.* (2002)). However, an attempt was made to make the data sets from different sources uniform. Only 48 of the 90 boreholes were selected to estimate the heat flow density. Of the 48 boreholes of this study, 11 are offshore boreholes, 32 are mining or water boreholes, and 15 are oil exploration wells.

Heat flow density is the fundamental quantity in geothermal studies. To calculate it, it is necessary to estimate the geothermal gradient in a borehole and multiply it by the thermal conductivity of the geological formations traversed by the borehole. The thermal conductivities of the rocks in the regions where the boreholes are located and some heat production values for main rock units can be found in Ramalho and Correia (2006).

2. GEOLOGICAL SKETCH OF PORTUGAL

Mainland Portugal has remarkable geological heterogeneity, with formations ranging from the Precambrian to the Quaternary, as illustrated in Figure 1. This variety leads to the existence of several geothermal zones, which depend on the geology and local and regional structural features. Mainland Portugal is divided into three major structural units, which, in turn, are divided into several zones according to geological and structural characteristics. The Hesperic Massif is a wide area composed of igneous and metasedimentary rocks from the Precambrian and Palaeozoic ages. This area comprises most of Portugal and the eastern part of Spain. The Portuguese part of the massif is also divided into several units with different geological characteristics and ages. The northern Portuguese part of the massif is mostly composed of granitoid rocks and schists. The NNE-SSW fault system of Régua-Verin-Penacova and the Vilariça fault (Ribeiro *et al.*, 1979) are the main structural features of the region. These fault systems are known to play an important role in the regional deep circulation of mineral waters, and springs are known to occur along them.

The southern part of the Portuguese segment of the Iberian Massif is formed by two geotectonic units: the Ossa Morena Zone (OMZ) in the northeast and the South Portuguese Zone (SPZ) in the southwest. These units are separated by a major overthrust trending NEE-SWW (Ferreira-Ficalho Overthrust - FFO) and dipping NE (Ribeiro *et al.*, 1979).

The OMZ is characterized by Precambrian and Lower Palaeozoic rocks showing intense deformation caused by different deformation phases with distinct trends and widespread volcanic synorogenic magmatism. In the NE part of the OMZ, there is a transitional domain where granitoid rocks give way to basic intrusions with dominant calcalkaline chemistry to the SW.

In the SPZ, the older rocks date from the Upper Palaeozoic, namely from the Upper Devonian. Volcanism is more acidic than in the OMZ. Plutonism is not significant, and metamorphism is low grade. However, there is conspicuous tectonic and palaeogeographic polarity between OMZ and SPZ.

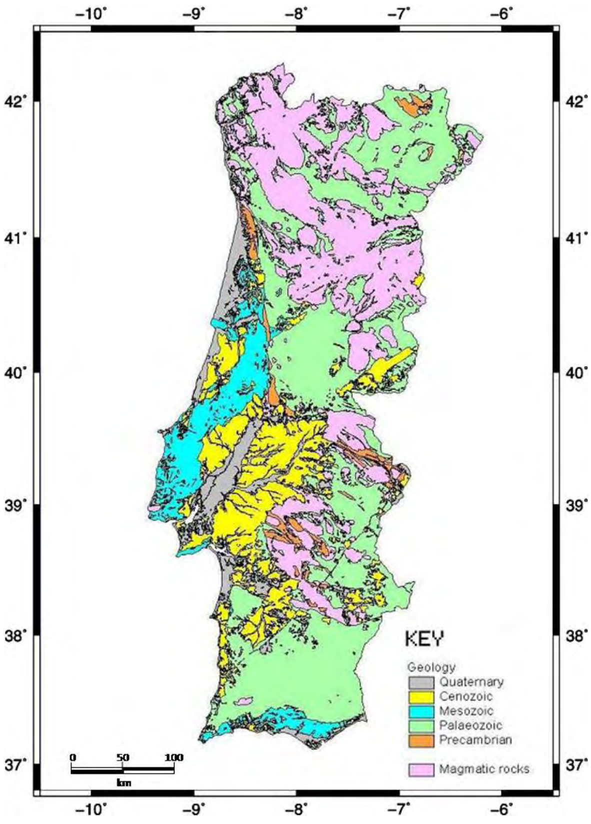

Figure 1: Simplified geological map of mainland Portugal.

The western and southern Meso-Cenozoic Borders were formed after Palaeozoic times and are mainly composed of sandstones and limestones that mark sea level oscillations during the Mesozoic and Cenozoic transgressions over the Hercynian continent. The existence of salt diapirs in the western Meso-Cenozoic Border strongly influences the existence of several hot springs, which show higher water flow and mineralization than in the Hesperic Massif. Both borders are controlled by fault systems and generally present good potential for the exploitation of deep-seated non-convective aquifers linked to permeable horizons.

The Lower Tagus and Sado River Tertiary basins are composed by Miocene and Pliocene sediments (sandstones and porous limestones), which reach depths of about 1400 m.

3. GEOTHERMAL GRADIENT

The geothermal gradient is the measurement of temperature variation with depth. Geothermal gradients were calculated from temperature logs measured in water and mining boreholes. Those that showed evidence of water circulation and those that were shallower than 100 meters were rejected. Temperatures were measured in the saturated zone at 5 or 10 m intervals using a platinum probe or a thermistor probe. In oil exploration wells, the geothermal gradient was calculated from bottom hole temperatures using the Dowdle and Cobb method (Dowdle and Cobb, 1975). Figure 2 shows the geothermal gradient map of mainland Portugal.

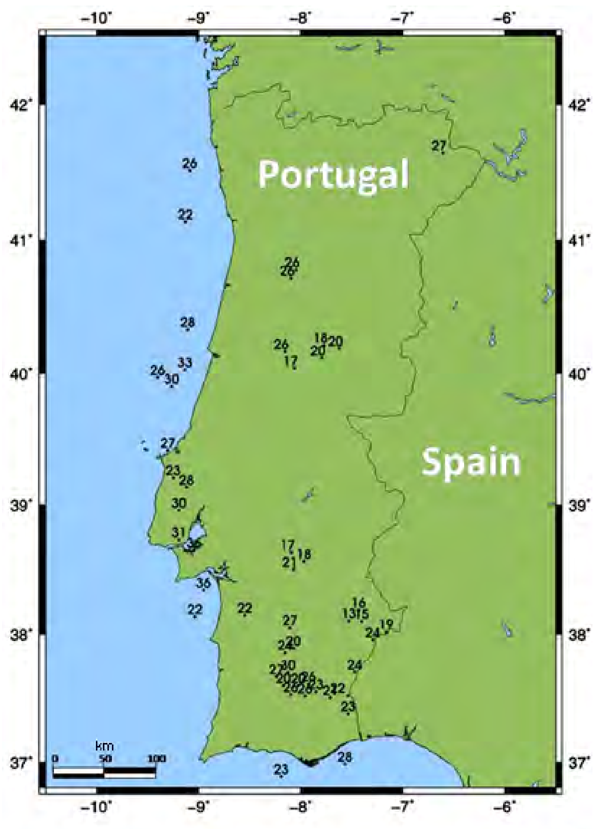

Figure 2: Geothermal gradient map for mainland Portugal. Values are in degrees Celsius per kilometer.

4. THERMAL CONDUCTIVITY

Thermal conductivity measurements were performed in cores from the boreholes (when available) and in rock samples from outcrops near the boreholes. When no cores or rock samples were available, thermal conductivities from the literature were assumed. For each borehole, the effective thermal conductivity (k_{eff}) was calculated using Equation 1:

$$k_{eff} = \frac{\sum_{i=1}^{n} \Delta z_i}{\sum_{i=1}^{n} \frac{\Delta z_i}{k_i}} \quad (1)$$

where i corresponds to different rock types, Δz_i is the thickness of the i^{th} rock layer, and k_i is the thermal conductivity of i^{th} the rock layer. Measured and assumed thermal conductivities used to calculate effective thermal conductivities for the boreholes of this study can be seen in Ramalho and Correia (2006).

5. HEAT PRODUCTION

To determine the heat production of a rock it is necessary to know its uranium, thorium, and potassium concentrations. For most rocks and cores from the boreholes reported in this study, these concentrations were obtained using a gamma-ray spectrometer with a NaI(Tl) scintillation detector. The heat production ($\mu W/m^3$) was calculated using the following expression (Rybach, 1976):

$$A = \rho\,(0.097\,C_u + 0.026\,C_{Th} + 0.036\,C_K) \quad (2)$$

where ρ is the rock density (g/cm^3) and C_U, C_{Th}, and C_K are the concentrations of U and Th (in ppm) and K (in %), respectively. For some boreholes, there are no experimental values for uranium, thorium and potassium concentrations. In these cases, heat production values were assumed from Rybach and Cermak (1982) for the rock types found in the boreholes.

6. HEAT FLOW DENSITY

A map of the heat flow density in mainland Portugal is given in Figure 3. The heat flow density values for water, mining, and oil wells were calculated by multiplying the average geothermal gradient of Figure 2 by the effective thermal conductivity for each borehole. For some oil wells, the heat flow density was calculated using the following expression (Camelo, 1987,a):

$$q = \frac{T_i - T_0}{\sum_{j=1}^{n} H_{ij} \frac{1}{k_j}} \qquad (3)$$

where n is the total number of layers in the oil well, H_{ij} is coefficient related to the thickness of the layer j from the surface to depth z_i, k_j is the thermal conductivity of layer j, T_i is the temperature at depth z_i, and T_0 is the temperature at the surface.

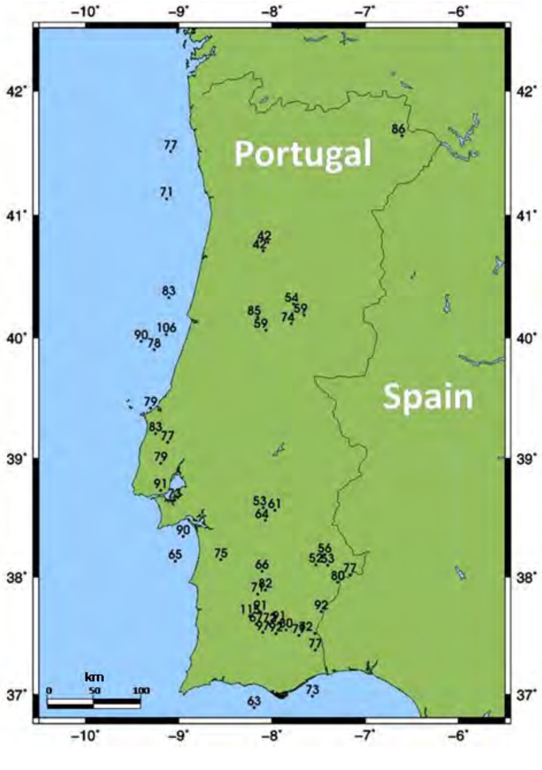

Figure 3: Heat flow density map for mainland Portugal. Values are in mW/m^2.

7. TEMPERATURE AT 500 AND 1000 METERS DEPTH

With the objective of estimating the temperature at different depths, the temperatures at 500 and 1000 m were calculated from the heat flow density values for each borehole using Equation 4:

$$T(z) = T_0 + \frac{q\,z}{k} - \frac{A\,z^2}{2\,k} \qquad (4)$$

where T(z) is the temperature at depth z in °C, T_0 is the temperature at the surface in °C, q is the surface heat flow density in W/m^2, k is the thermal conductivity in W/m-K, and A is the heat production in W/m^3. The temperature at 500 and 1000 m depths are shown in Figures 4 and 5, respectively.

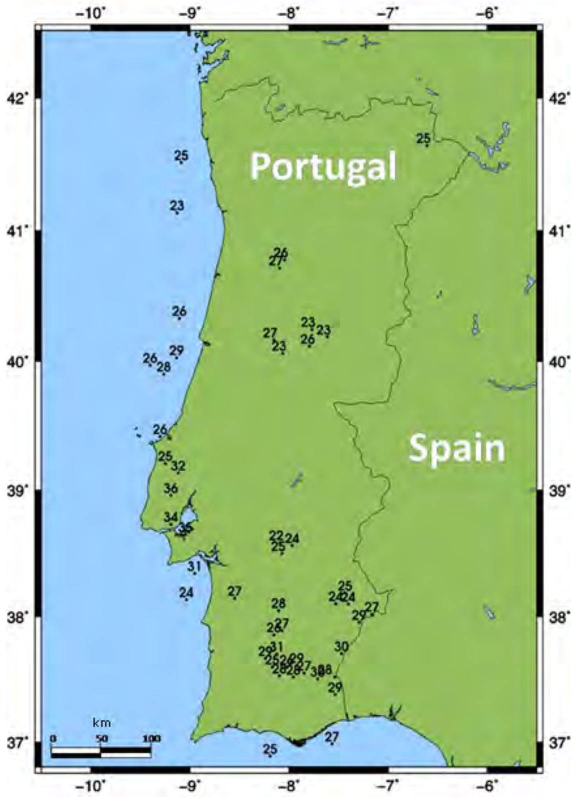

Figure 4: Temperature at 500 m depth for mainland Portugal. Values are in °C.

8. CRUSTAL MODELING FOR SOUTHERN PORTUGAL

From the heat flow density map, it is obvious that the highest concentration of boreholes is located in the southern part of Portugal. All offshore wells and a few onshore wells are for oil; all others are mining or water wells. The southern part of Portugal used to be an area of intense mining activity, which helped to find opportune boreholes to measure temperatures. Heat flow density estimates in mining and water wells are more reliable than in oil wells because of the kind of information that can be obtained in the boreholes. In the former, temperatures are obtained with probes as precise as 0.004 K, while in the latter, the temperature data are basically bottom hole temperatures with precisions of about 0.1 K. With this in mind, a two-dimensional geothermal model of the crust in southern Portugal was attempted with the objective of estimating the thermal regime of the crust.

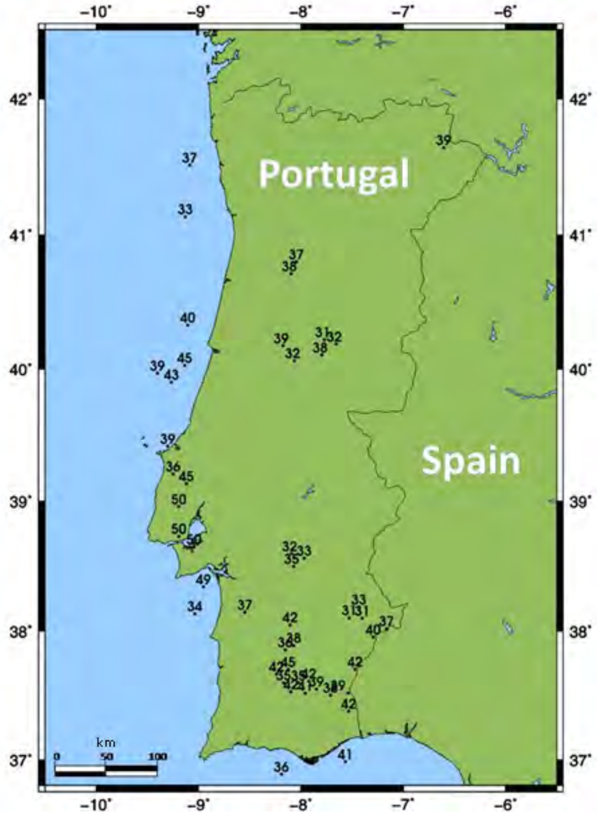

Figure 5: Temperature at 1000 m depth for mainland Portugal. Values are in °C.

8.1 Two-dimensional Thermal Model

A NS profile was chosen for the construction of a two-dimensional model in the southern part of mainland Portugal, which crosses the OMZ and SPZ. Its length is 360 km, and its position is shown in Figure 6.

The depth of the profile (30 km) coincides in the OMZ with the thickness of the crust, while in the SPZ, the depth of the Moho boundary is slightly shallower (29 km). From the point of view of geothermal modelling, the most relevant difference between the OMZ and SPZ is the observed surface heat flow, which is about 60 mW/m^2 in the OMZ and ranges from 70 to 90 mW/m^2 in the SPZ. This difference is well supported by heat flow density estimates.

Interpretations of several seismic refraction surveys (Mendes-Victor *et al.*, 1993) have suggested that the OMZ has a three-layer structure: a 12 km thick upper crust with an average seismic velocity 6.1 km/s, an 11 km thick middle crust with a velocity of 6.3 km/s, and a 7 km thick lower crust with a velocity of 6.8 km/s. The SPZ also seems to have a three-layer structure: a 14 km thick upper crust with a velocity of 6.1 km/s, a 7 km thick middle crust with a velocity of 6.2 km/s, and an 8 km thick lower crust with an average seismic velocity of 7.0 km/s. This structure of the two geological units was used to construct the two-dimensional geothermal model shown in Figure 7.

The heat productions of the upper, middle and lower crust of both the OMZ and the SPZ were estimated using the empirical relationship between radiogenic heat production and compressional seismic velocity proposed by Rybach and Buntebarth (1982, 1984):

$$\ln A = 12.6 - 2.17 \cdot V_P \qquad (5)$$

where A is the heat production in mW/m^3 and Vp is the seismic velocity of compressional waves in km/s. The resulting heat production model is shown in Figure 7. Thermal conductivity values for both the OMZ and the SPZ are taken from Correia and Jones (1995) and are 2.7, 2.5 and 2.1 W/mK for the upper, middle and the lower crust, respectively, as shown in Figure 7. To calculate the temperature along the profile, the variation of thermal conductivity with pressure and temperature was considered by using the following expression:

$$k(T, z) = k_0 \cdot (1 + c \cdot z)/(1 + b \cdot \Delta T) \qquad (6)$$

where T is the temperature in °C, k_0 is the thermal conductivity at 0°C and 1 atm pressure, and b and c are constants.

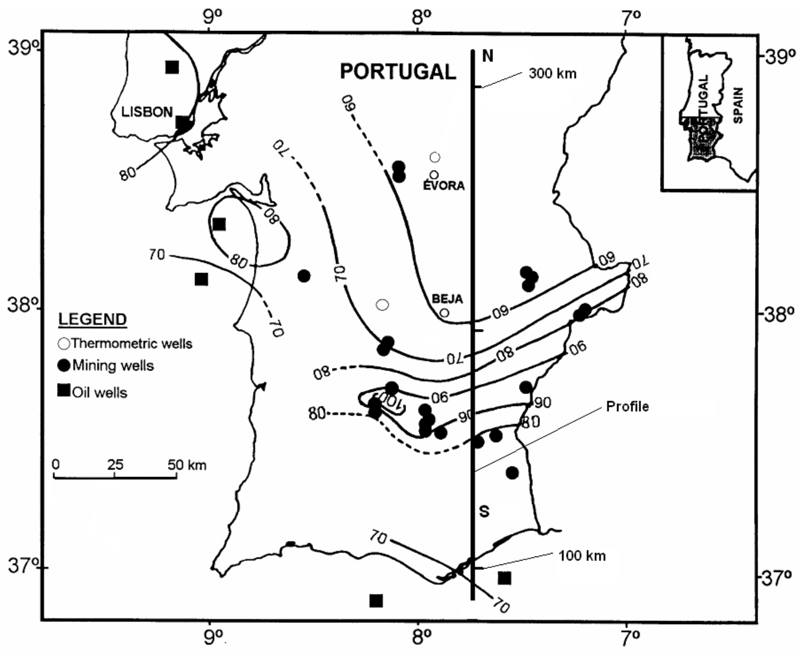

Figure 6: Profile along which the two-dimensional thermal model was constructed.

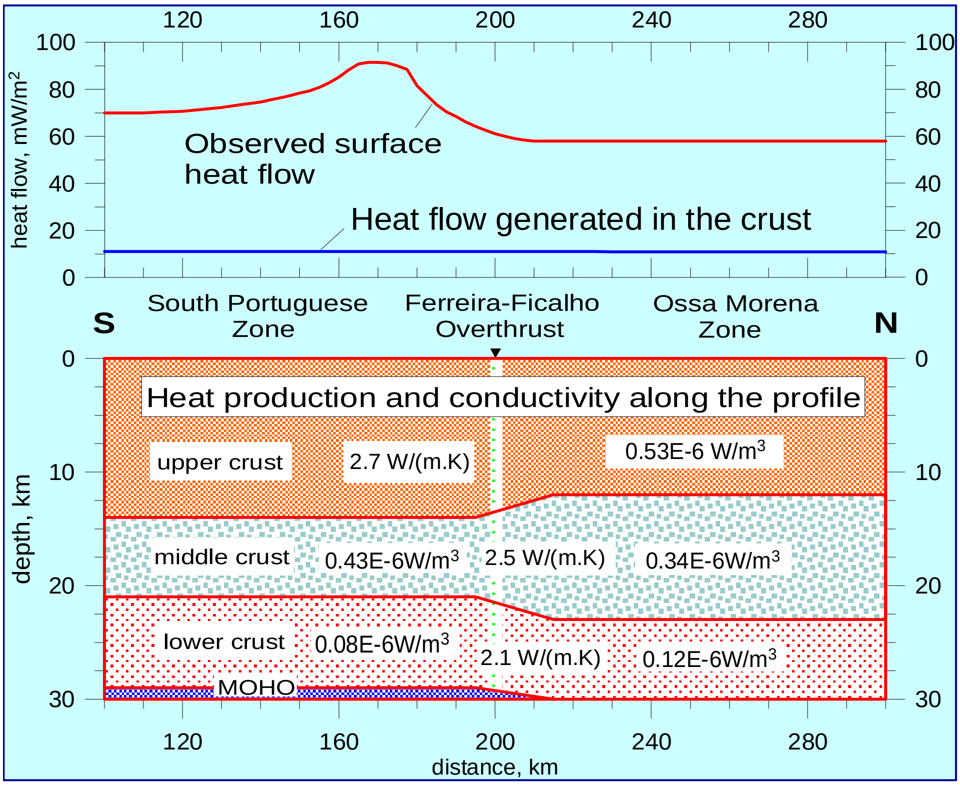

Figure 7: Two-dimensional thermal model along the NS profile shown in Figure 6.

Figure 8 shows the distribution of temperature in the crust along the profile of Figure 6 as a result of the model of Figure 7. At Moho depths the two-dimensional model indicates that the temperature in the SPZ (to the south) is higher about 50 degrees Celsius than in the OMZ (to the north). To calculate the temperature profile shown in Figure 8, the value of 33 mW/m^2 was chosen for the Moho mean heat flow density.

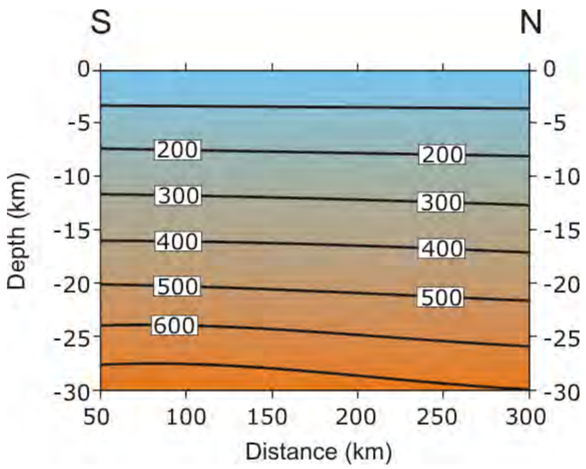

Figure 8: Distribution of temperature along the profile presented in Figure 6. Values in °C.

9. DISCUSSION AND CONCLUSIONS

The HFD values for mainland Portugal vary from 40 to 115 mW/m^2, with an average value of about 75 mW/m^2. HFD values in the northern regions of the Hesperic Massif range from 65 to mW/m^2. In the northern part of the massif the heat flow density increases.

In the SPZ, regional HFD values reach about 90 mW/m^2, while in the OMZ, values are only about 60 mW/m^2 and are similar to HFD values obtained for other European hercynian regions. In the sedimentary basins, regional HFD values range from about 40 to 90 mW/m^2.

Numerical modeling along a two-dimensional profile of the crust in southern Portugal provided estimates of crustal temperatures in the two main geotectonic units of the region. Contrary to previous one-dimensional modelling carried out by Correia and Ramalho (1999), the calculated Moho temperatures do not exceed 700°C in the model configurations considered and are consistent with the other geophysical and geological data and the results of a detailed deep magnetotelluric survey in particular (Correia and Jones, 1997, Jones and Correia, 1999). Temperatures range from 400 to 500°C in the Ossa-Morena Zone and 500 to 670°C in the South Portuguese Zone. The comparison of Moho temperatures resulting from the different model configurations suggests that the uncertainty of the calculations is in the order 50–100°C.

Based on this geothermal and geological information, a preliminary HFD zoned map is presented in Figure 9 that is intended to be used for geothermal exploitation purposes. Four HFD zones are delineated, but the HFD values for different areas have different degrees of accuracy, with the northern values being the less accurate due to the lack of sufficient information. The map presented in Figure 9 can be used in geothermal studies at a national scale. This map must be updated and detailed as more geothermal data are collected.

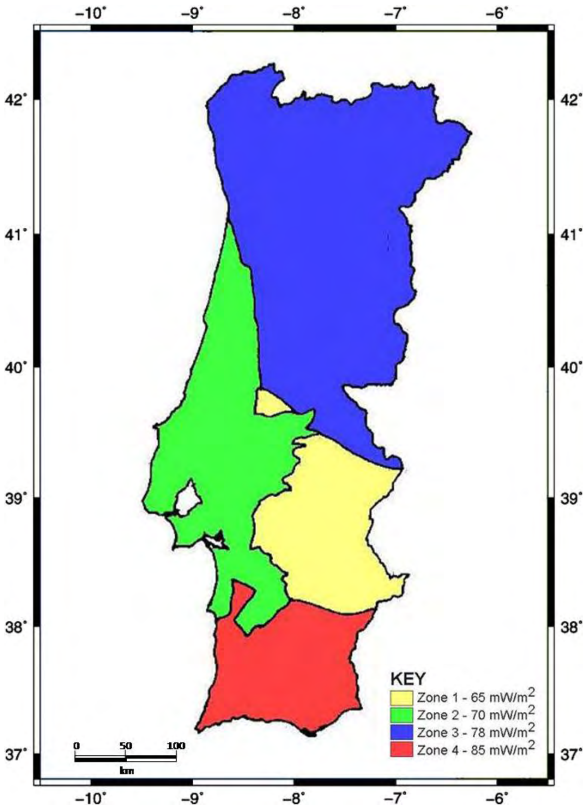

Figure 9: Heat flow density zones for mainland Portugal based on HFD values shown in Figure 3 and geological and structural features (Correia and Ramalho, 2005).

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