

## Updated Surface Heat Flow Density Map in Mainland Portugal

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### ABSTRACT

The collection and use of geothermal information to draw a heat flow density (HFD) map and determine the geothermal regime of the crust for mainland Portugal began at the end of the seventies. The data have been collected from all the available scientific publications and internal reports of Portuguese institutions that have been working in the geothermal field. Recent data have also been obtained by the authors to make studies on crustal geothermal modeling and palaeoclimatology.

Due to the existence of large granitic regions in northern Portugal, with long faults in several directions, surface heat flow density estimations for that area are difficult to obtain. Furthermore, most of the wells drilled there are shallower than 120 m. However, many of the Portuguese thermal springs are located in that region. On the other hand, intensive mining in southern Portugal has created a large and reliable HFD data set for the region. In most Portuguese sedimentary basins, geothermal data come from deep oil prospecting wells.

All the geothermal information collected up to now in mining, water and oil wells that were considered appropriate to calculate surface heat flow density are shown as an updated HFD map of mainland Portugal. It also includes surface HFD values obtained using geothermometry techniques applied to thermal waters with deep circulation. The updated surface HFD map is compared with the Portuguese geological map. Based on those data, a map with different HFD zones is presented. This map could be used for geothermal exploitation purposes at national scale.

In general terms the HFD values for mainland Portugal range from 40 mW/m<sup>2</sup> to 115 mW/m<sup>2</sup>, with an average value of about 75 mW/m<sup>2</sup>.

### 1. INTRODUCTION

Developments in geothermal exploitation methods have been recently tested in Portugal (Carvalho, 2004). One of the basic parameters used in geothermal prospecting is the heat flow density (HFD). The collection and use of geothermal information to draw a HFD map and determine the geothermal regime of the crust in mainland Portugal is a task that has been carried out since the late 70's; this map is being continuously updated as more geothermal information from wells is collected and considered suitable for HFD estimations (Ramalho and Correia, 2004; Correia *et al.*, 2002).

This geothermal diversity can be seen in Fig. 1 where fifty two low enthalpy thermal occurrences, unevenly distributed

throughout the country, with temperatures ranging from 20 °C to 76 °C are shown for Mainland Portugal. The most important ones, with high temperatures and balneotherapeutic characteristics, are located in the northern part of the country, in the so-called Centro-Iberian Zone (CIZ) geotectonic unit of the Hesperic Massif (Fig. 1). Most of them emerge in crystalline rocks with the water flowing through local and regional fault systems. Chemical characteristics of the water vary from place to place (Fig. 1): on average, low mineralised sulphureous and bicarbonate waters are common in the Hesperic Massif, while highly mineralised waters, chloride and sodium rich, occur in the Meso-Cenozoic Basins (Cruz *et al.*, 1996).

### 2. GEOLOGICAL SETTING

Mainland Portugal has a remarkable geological heterogeneity with formations ranging from the Precambrian to the Quaternary (Fig. 2). 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 (Fig. 2). The Hesperic Massif is a wide area composed by igneous and metasedimentary rocks from Precambrian and Palaeozoic age. This area comprises most Portugal and the eastern part of Spain. The Portuguese part of the massif is also divided into several units (Fig. 2) with different geological characteristics and ages. The Portuguese northern part of the massif is mostly composed by granitoid rocks and schists. The NNE-SSW fracture system Régua-Verin-Penacova and the Vilarica 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, with the occurrence of springs along them.

The southern part of the Portuguese segment of the Iberian Massif is formed by two geotectonic units: the Ossa Morena Zone (OMZ) to the northeast and the South Portuguese Zone (SPZ) to the southwest; these units are separated by a major overthrust trending NEE-SWW 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 place to basic intrusions with dominant calc-alkaline chemistry to the SW.

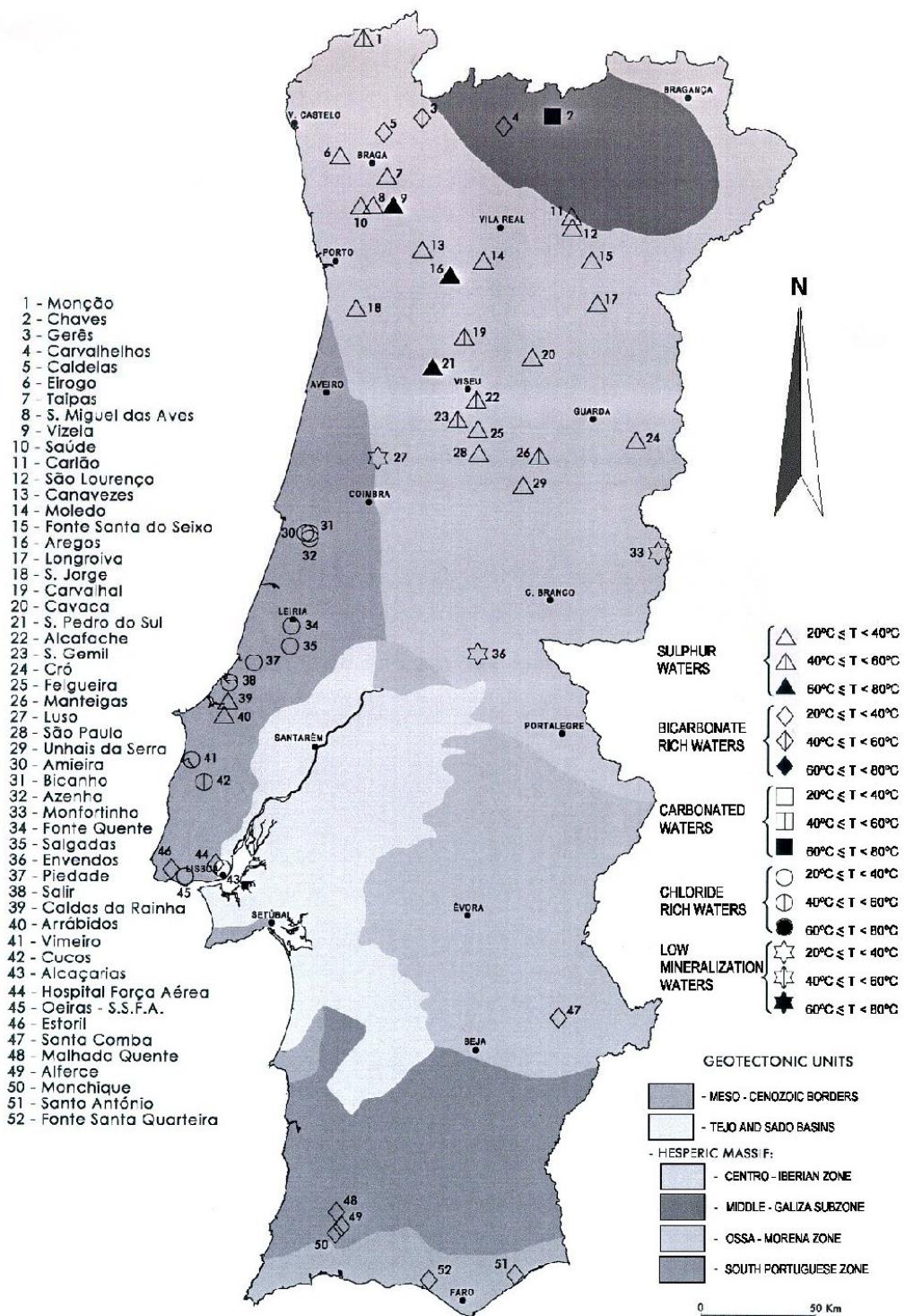
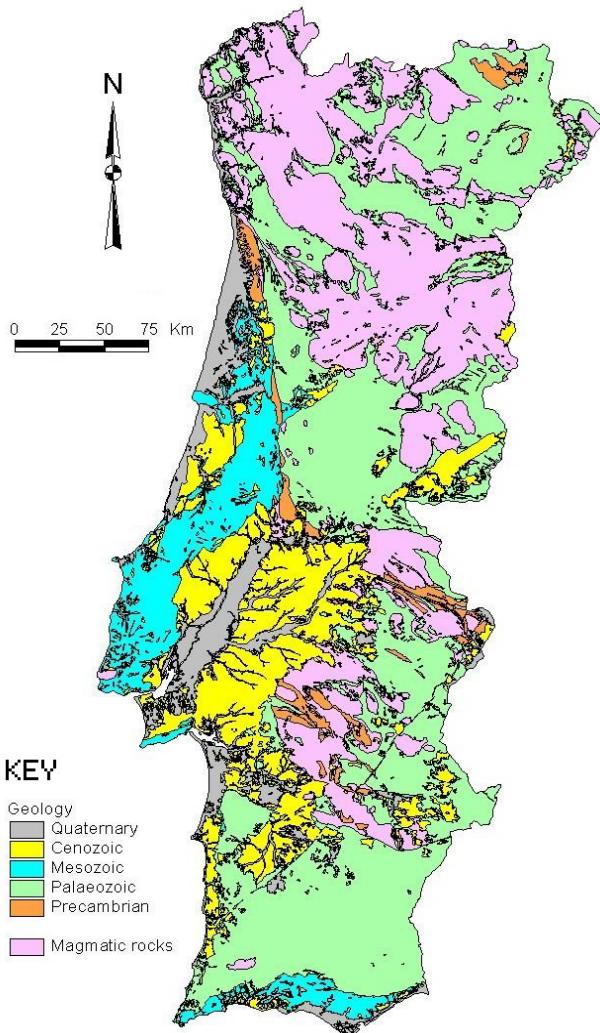


Figure 1 – Thermal occurrences and geotectonic units in Mainland Portugal (from Ramalho *et al.*, 1999).



**Figure 2: General geology of Mainland Portugal.**

In the SPZ, however, the older rocks date from the Upper Palaeozoic, namely from the Upper Devonian. Volcanism is more acid than in the OMZ. Plutonism is not significant and metamorphism is low grade. There is though a conspicuous tectonic and palaeogeographic polarity between OMZ and SPZ.

The western and southern Meso-Cenozoic Borders were formed after Palaeozoic times and are mainly composed by sandstones and limestones that mark sea level oscillations during the Mesozoic and the following Cenozoic transgressions over the Hercynian continent. The existence of salt diapirs in the western Meso-Cenozoic Border has a strong influence upon several hot springs, which show higher water flows and mineralisations than in the Hesperic Massif. Both borders are controlled by several fault systems and, in general, they are good prospects for the exploitation of deep-seated aquifers of non-convective type linked to permeable horizons.

The Lower Tagus and Sado Rivers Tertiary basins are composed by Miocene and Pliocene sediments (sandstones and porous limestones), which reach depths not deeper than 1400 m.

### 3. HFD ESTIMATIONS

As previously stated, the complex geological structure of mainland Portugal makes the estimation of HFD values difficult in some regions. For instance, in the Centro-Iberian

Zone heat flow density values are difficult to estimate because most of the wells are too shallow (less than 100 m deep) for reliable HFD calculations. On the other hand, the amount of deep mining wells located in the Iberian Pyrite Belt in the South Portuguese Zone make HFD estimations easier and statistically representative. Figure 3 shows the location and the type of all the wells and thermal springs used to estimate the HFD values presented in this study; some of the HFD values calculated for all those locations had to be rejected because the values did not comply with pre-defined reliability criteria. Figure 4 shows the location of the sites where reliable HFD values were calculated after application of the methods described in the following subsections.

#### 3.1 HFD estimations in mining, water and geothermal wells

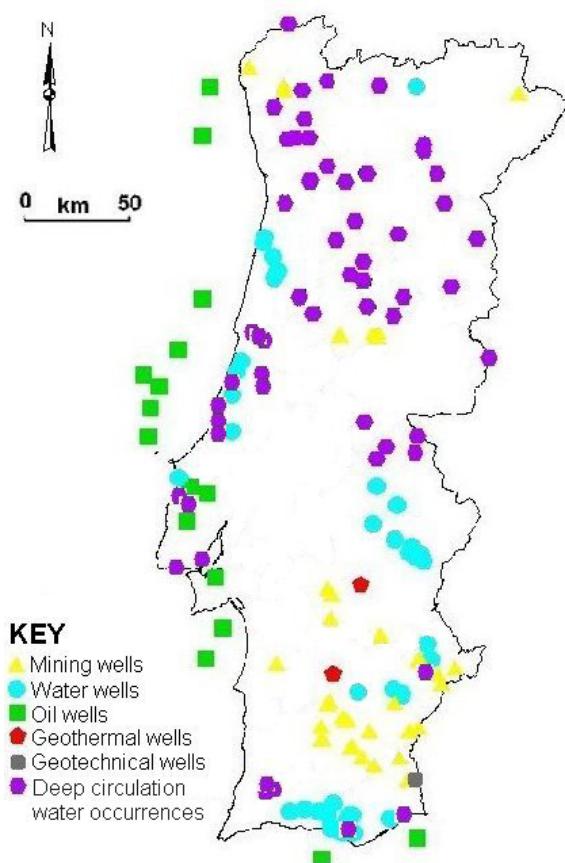
Surface HFD in mining, water and geothermal wells is calculated multiplying the average geothermal gradient obtained in a well by the thermal conductivity of the geological formations crossed by the well. When determining HFD in these wells it is assumed that the formations crossed by the well are laterally homogeneous and isotropic, and that the thermal conductivity is independent of temperature. It is also considered that heat transfer is by conduction and stationary. The effects of heat production by radioactive decay of thorium, uranium and potassium are also considered. In these wells, HFD is calculated through the equation:

$$q = k \text{ (grad T)} \quad (1)$$

where  $q$  ( $\text{W/m}^2$ ) is the HFD,  $k$  is the thermal conductivity ( $\text{W/mK}$ ),  $(\text{grad T})$  is the vertical geothermal gradient ( $\text{K/m}$ ), usually represented in  $^{\circ}\text{C/km}$ . Most times the unit  $\text{mW/m}^2$  is used as a practical unit for HFD.

For this study all data considered reliable for heat flow density estimations had to satisfy several constraints concerning physical characteristics of the wells, number of temperature measurements in the well, precision of the temperature measurements, and borehole stability criteria (Ramalho and Correia, 2004).

Temperature data were collected from different sources. Selected wells were initially studied by Almeida (1992), Duque (1991), Ramalho (1997); some of them are wells in which temperature measurements were carried out by Almeida (1992) and processed as described in detail in Ramalho and Correia (2004). For those wells where thermal conductivity measurements were available (Duque, 1991; Almeida, 1993), the effective thermal conductivity was calculated using those values; otherwise, assumed thermal conductivities were assigned to the rocks, based on measured values obtained in other samples of the same rock type of nearby wells or, if the thermal conductivity of the formations is not known, average values mentioned in literature (for instance, in Cermak and Rybach, 1982) were used. In the wells where no lithology was available, assumed thermal conductivity was the same as considered in Fernandès *et al.* (1995; 1998).



**Figure 3:** Location of all sites where geothermal measurements were made. Many data from water wells were rejected due to stability and precision criteria requirements.

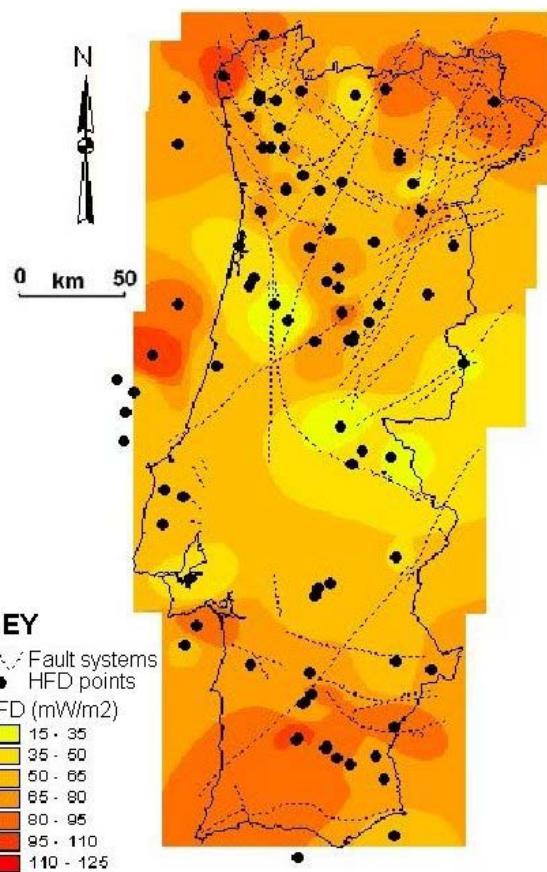
### 3.2 HFD estimations in oil wells

In sedimentary basins HFD was estimated using bottom-hole temperatures obtained in on-shore as well as off-shore oil prospecting wells (Camelo, 1987; Duque, 1991). Effective conductivities were estimated from lithology logs, attributing a specific thermal conductivity value to each lithology (Camelo, 1987).

### 3.3 HFD estimations with silica geothermometers

In the CIZ most water wells only penetrate the weathered zone and so only small depths are reached creating a problem of reliability in the HFD estimations. Furthermore, deep mining wells are scarce and irregularly distributed. However, more than thirty mineral water occurrences, with deep circulation, emerge in crystalline rocks with the water flowing through local and regional fault systems. Most of these waters are low mineralised bicarbonate-sulphate waters (Cruz *et al.*, 1996). Even though this number is small, it is considerably higher and more evenly distributed than conventional HFD estimations for the same area. Therefore, the silica ( $\text{SiO}_2$ ) geothermometer equation developed by Truesdell (1976) was applied to those waters with deep circulation and long residence time. The relation between temperatures obtained through silica geothermometry and deep thermal conditions obtained from wells studied by Almeida (1992) and Duque (1998) was the empirical 1st degree linear equation:

$$\text{TSiO}_2 = 0.647 q + 66.804 \quad (2)$$



**Figure 4:** HFD estimation points used in this study. Faults are also represented as broken lines.

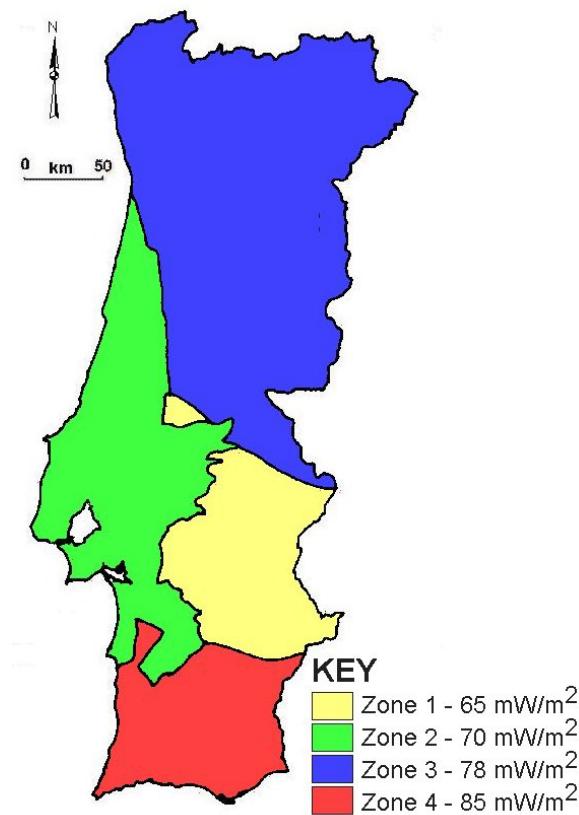
The HFD values obtained by applying this method were however used with caution because the number of HFD values and silica geothermometry temperatures are still scarce. Work on this subject is still going on.

## 4. CONCLUSION

The HFD values for mainland Portugal vary from  $40 \text{ mW/m}^2$  to  $115 \text{ mW/m}^2$ , with an average value of about  $75 \text{ mW/m}^2$ . HFD values for the CIZ of the Hesperic Massif range from  $65 \text{ mW/m}^2$  to  $80 \text{ mW/m}^2$ . In the northern part of the massif there is a HFD increase.

In the SPZ, however, regional HFD values reach about  $90 \text{ mW/m}^2$ , while in the OMZ these values decrease to about  $60 \text{ mW/m}^2$ , which are similar to HFD values obtained for other European hercynian regions. In the sedimentary basins, regional HFD values range from about  $40 \text{ mW/m}^2$  to  $90 \text{ mW/m}^2$ .

Based on this geothermal and geological information a HFD zoned map to be used for geothermal exploitation purposes is presented (Fig. 5). Four HFD zones are delineated; however, the HFD values for different areas have different degrees of accuracy, the northern values being the less accurate due to the lack of sufficient information. The map presented in Fig. 5 can be used in geothermal studies at national scale. This map must though be updated and detailed as more geothermal data are collected.



**Figure 5: HFD zones based on HFD average values and geological and structural features of mainland Portugal.**

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