Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Speaking About Heat Flow Density Maps

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Keywords: Heat flow maps, Curie Point Depth, Crustal heterogeneity, Radioactive heat sources, Thermal conductivity values

ABSTRACT

The conventional method of creating maps of heat flow values uses data obtained in boreholes, lakes and / or galleries of mines. Due to uneven geographical distribution of data it is necessary to use average values in some regions and to try to obtain information in other regions using indirect methods. In order to obtain more detailed information, aeromagnetic data have been used to find the Curie depth and through Curie point temperature to obtain information about the temperature gradient and the heat flow in the region. As the methods mentioned are based on completely different techniques, it is natural that the results obtained are not exactly coincident. There are, however, regions where the results obtained are contradictory. This work analyses some of the problems that arose using as an example the Northern region of Portugal and part of Galicia region in Spain. It is a region with a very heterogeneous upper crust and where hot water reservoirs were detected. Curie point depths achieved with temperature values obtained from measured heat flow density values are higher (values from 1 Km to 5 Km) than values found from magnetic data.

1. INTRODUCTION

The spatial distribution of the heat flow in the Earth's surface is a very important datum because from it it is possible to study the thermal state of the interior of the Earth and the heat losses through its surface. Detailed heat flow maps also allow to understand the thermal status of specific individualized regions. Local heat flow anomalies can be a very important element in the detection of some terrestrial resources (e.g. pyrite deposits) or regions that could be used for the production of electricity (hot dry rock) or other types of geothermal applications.

The conventional method of creating maps of heat flow density values uses data obtained in boreholes, lakes and/or galleries of mines. This work consists in the measurement of temperatures and thermal conductivities of the formations traversed by the boreholes at different depths. As the heat flow measured at the surface results from the sum of the heat flow from the mantle with the heat flow originated by the thermal sources in the crust, it is necessary to know the production of heat in the region due to the decay of existing radioactive elements and other thermal sources that may exist to extend the study to deeper depths. Due to uneven geographical distribution of data it is necessary to use average values in some regions and to obtain information on another regions using indirect methods. Aeromagnetic and magnetic data have been used in last decades to obtain the Curie depth and through Curie Point temperature to obtain temperature thermal gradient and heat flow density values in the region or in the global Earth surface. Some problems can be associated with this type of methods. The temperature of the Curie point depends on the chemical composition of the medium. The Curie point temperature of magnetite at atmospheric pressure is the most used value, 580 °C. In the global model, the value 550° C was used. The Curie Point Depth (CPD) has been obtained using spectral methods. Different methods have been used to make the inversion from the magnetic anomalies but all of them are based on assumptions of flat horizontal layers with random magnetization distribution or flat layers with fractal magnetization distribution. Salem et al. (2014) used a "de-fractal" method where the power spectral density of the random magnetization model is multiplied by a factor $k^{-\alpha}$ (k is the radial wavenumber and α is the fractal index related with the fractal parameter of magnetization $\alpha=\beta-1$). There are some problems associated with the use of these methods. Assuming that no problems occurs with magnetic data acquisition and processing, the more frequent problems are related with window size inadequate for vertical resolution and regions that differ from model assumptions due to more than one geological regime in one window like regions associated with different fractal parameters from the value assumed or different sources of magnetization or different distribution of the sources. The value of the β used is another problem of difficult resolution.

The thermal gradient value is obtained considering a uniform region , from the top of the crust to the Curie Point depth. This means that no heat sources in the crust are considered and an average thermal conductivity value is used. No difference is made between regions with upper crust formed by igneous acid or basic rocks or regions with thick layers of sediments. The average thermal conductivity values used by different authors can be very different. Values of K = 2.0 W $K^{-1}m^{-1}$ for oceans and K = 2.5 W $K^{-1}m^{-1}$ for continents are used by Li and Wang (2017) to model global Earth, a value of K = 2.8 W $K^{-1}m^{-1}$ was used for Antarctica by Martos et al. (2017), a value of K = 2.2 W $K^{-1}m^{-1}$ was assumed for the Iberian Peninsula by Andrés et al (2018). The use of different values for the same parameter or property makes very difficult to compare the results obtained.

The analysis of data obtained with the two approaches presented shows that research must be made trying to obtain more knowledge about the crust in the regions on study using different methods like those using seismic and gravity data. Gamma radiation charts can also give information related with heat source distribution in the region. Heterogeneities in the crust must be introduced in thermal models if they are detected by other methods.

An example is described in sections 2 and 3 to show the application of two different methods in a region where crustal heterogeneity is know from seismic data and non uniform distribution of heat sources is known from the content of radioactive elements in the region and gamma ray charts.

2. NORTHERN PORTUGAL AND SOUTHWESTERN OF GALICIA

This region was chosen to compare the results obtained using magnetic data and measured heat flow density values due to intensive knowledge of upper and middle crustal structure obtained from seismic P waves velocity using vertical profiles and horizontal distribution at different depths (Veludo et al., 2017). An intensive study of the content of radioactive elements Uranium, Thorium and Potassium in granites of Northern and Central Portugal (Lamas et al., 2017) makes possible to obtain heat source distribution near the surface, in the region.

2.1 The region studied

The region on study is located in the NW of the Iberian Peninsula between latitudes 41.4 N and 42.4 N and longitudes 6.0W and 8.5 W. It is a region with an heterogeneous crust but a detailed analysis of the structure and thickness of the different layers of the upper and middle crust is available for the region, Veludo et al (2017) as a detailed analysis of radioactive heat sources, Lamas et al (2017).The western part of the region is characterized by the existence of granites with different ages and different thickness and high contents of radioactive elements Uranium, Thorium and Potassium. Hot springs and aquifers may be found in the region. In the Southeastern part of the region the gamma-ray chart shows two negative anomalies located in Morais Massif and Bragança Massif. These regions are formed by different types of basic rocks with low values of thermal conductivity and low values of heat sources. The Morais massif is formed by three allochthonous units called Superior Allochtone complex formed by continental crust, the ofiolithic complex formed by oceanic crust and the inferior allochthonous complex formed by material of a continental margin suffering rupture (continental margin of Gondwana). Different values of Moho depth are found in the region due to the existence of crustal blocks delimitated by deep faults in the region (Dundar et al., 2016 ; Mancilla et al, 2015).

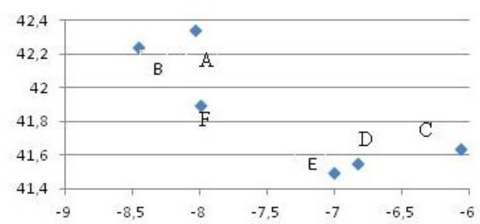
2.2 Curie Point Depth (CPD) in the region

CPD values for the region may be obtained from two different works. A global reference model of CPD values based in a global magnetic dataset EMAG2 presented by Li et al. (2017) and a work made for the Iberian Peninsula presented by Andrés et al. (2018). The methodology used in both works assumes a fractal magnetization of the crust but Li et al. (2017) used a constant fractal exponent of 3 and Andrés et al (2018) used a methodology presented by Salem et al. (2014) to constrain the fractal para meter. In the region of our study, the NW of Iberia the value chosen was 4 (the highest value used in the work). CPD values presented by Li et al (2017) for NW Iberia are <30 Km and values presented by Andrés et al (2018) are 26 Km in the Northeast of Portugal and in the interval 23-24 Km in the Nortwestern part of the region studied (points A and B of this work).

Heat flow density values obtained by Li et al (2017) are in the interval 60-90 mW m^{-2} and the values presented by Andrés et al (2018) are 64 mW m^{-2} in the Northeast of Portugal and 64 to 68 mW m^{-2} in the northwestern part (points A and B of this work).

2.3 Heat flow density values and thermal data

Measured heat flow density values in the region are scarce but it was possible to use 6 values of heat flow density in this work. Three of them were obtained using the method presented by Duque, M. (2018 , 2019) with heat production in the region and layers thickness and crustal depths obtained from seismic data (Veludo et al.,2017: Dundar et al, 2016). Heat production values in superficial layers from radioactivity can be obtained by Uranium Thorium and Potassium content in the granites of the region published by Lamas et al (2015; 2017) and gamma-ray charts. The heat flow at the surface is obtained by the addition of the heat flow generated by crustal heat sources to heat flow from the mantle to the crust. The location and identification of the different points in our study can be seen in figure 1.



	Q_o (mW m^{-2})	K_o (W K^{-1} m^{-1})	A_o (μW m^{-3})
A	95	3.27	4.5
B	81	2.76	3.6
C	86	3.2	2.9
D	62	2.4	0.8
E	75	3.0	1.8
F	94	3.27	5.0

Figure 1: Heat flow density data location and table with heat flow , thermal conductivity and heat sources due to radioactivity (values obtained at the surface).

3. TEMPERATURE VALUES AT CPD AND MOHO DEPTH

Temperature values at depth were obtained considering heat conduction in the vertical direction in a region with different layers. Each region is characterized by a thermal conductivity value and a heat production value. The temperature at the surface (upper boundary condition) used is T(z=0) = 15 °C. Thermal conductivity value under the upper layers is 2.5 W K^{-1} m^{-1} and in the lower crust is 2.1 W K^{-1} m^{-1}. A heat production of 2 µW m^{-3} for layers under superficial data and 0.1 µW m^{-3} for the lower crust were used. No heat sources in the mantle were considered.

The model used for point A and some results obtained can be seen in figure 2.

Depth(Km)	K(W K^{-1} m^{-1})	A(µW m^{-3})	
0			
	3.27	4.5	Heat flow at the surface – 95 mW m^{-2}
7			
	2.5	2.0	Heat flow from the mantle – 35.1 mW m^{-2}
18			Heat flow due to crustal heat sources – 59.9 mW m^{-2}
	2.4	1.9	
21			Temperature at Moho depth (28 Km) -582.1 ° C
	2.1	0.1	
28			

Figure 2: Model used to obtain temperature depth of the Curie Point with value A, and some results obtained

The results obtained are summarized in Figure 3 where CPD means values obtained from magnetic anomalies, Δ T are the difference between 580° C (temperature of Curie Point) and temperature values found in our work at CPD values, ΔT_{Moho} are differences between Moho temperature values calculated from gradient temperature values obtained from CPD values considering a linear increase in temperature from the surface to Moho depth values and Moho temperature values obtained from measured heat flow density values, Z(580°c) is the depth where temperature values of 580°C were obtained in our work. The value found for B is higher than Moho depth and the value found in A coincides with Moho depth in the region. The other values found are lower than Moho depth but the value found in F presents a deviation of only 0.5 Km.

	CPD (Km)	ΔT (° C)	ΔT_{Moho}	Z(580° C)
A	25	48.2	67.5	28
B	24	80.3	109.7	29
C	26	59.3	92.1	29.5
D	26	17.8	50.9	27
E	26	51.1	84.2	29
F	26	60.0	81.8	29.5

Figure 3: Differences between temperature values for CPD and at Moho depth values in the region

The results obtained show that in the values found for Curie Point Depth, temperature values are lower than the value of the temperature used for Curie Point Temperature (580°C). The highest value of ΔT_{Moho} , 109.7 ˚C, was obtained in a region characterized by the existence of hot water in sufficient quantities to change the propagation velocity of the P seismic waves, the thermal conductivity and the heat production of the crust in the region. The lowest value, 50.9 ˚C, was obtained in a region with the lowest value of thermal conductivity and heat production in the crust and without thermal springs.

Heat flow density values obtained from CPD values, considering a Curie temperature of 580°C and an average conductivity are lower than measured heat flow density values. The interval between the maximum and minimum values measured, 33 mW m^{-2}, is higher than the value found using magnetic data , 4 mW m^{-2}. This difference can be related with thermal conductivity and heat production values used for the region and also to the assumption of homogeneity in the window used to obtain CPD values.

4. CONCLUSIONS

The method using magnetic data presents some problems related with the CPD determination and problems associated with density thermal gradient and heat flow density values obtained. Problems like Curie Temperature values are not solved and the assumption of homogeneity is not valid in many situations. Heat sources in the crust are not considered in many works which means that heat sources in the Earth are present only in depth deeper than CPD values. Measured heat flow density values are scarse in many regions and values of thermal conductivity and heat production need to be studied in detail .Special attention must be given to heterogeneous regions specially those with the presence of water. Changes in thermal gradient and thermal conductivity data must be present.In order to obtain reliable results all the information related with crustal structure and thermal parameters in the region must be used. At present heat flow maps can not be substituted by magnetic data. They do not given information related with upper parts of the crust.

The example presented show that measured heat flow density values are higher and present a greater dispersion than values obtained from CPD data. Temperature values obtained from measured data at CPD values are lower than 580°C. Values from 1 Km to 5 Km must be added to CPD values to obtain Curie Temperature values. Moho temperature obtained from CPD value are higher than values obtained from measured heat flow data. The differences found are higher in heterogeneous regions with water in the upper crust (109.7° C).

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