Vol. 07, No. 2 (2025) 1013-1020, doi: 10.24874/PES07.02A.009

Proceedings on Engineering Sciences

www.pesjournal.net

NONCONVENTIONAL METHODS USED TO STUDY EARTH´S THERMAL PROPERTIES INCLUDING GEOTHERMAL HEAT FLOW

Maria Rosa Duque[1]

Received 29.08.2024.
Revised 23.12.2024.
Accepted 17.01.2025.

Keywords:

Heat flow, Heat sources, V_P/V_S ratio, Thermal conductivity, Nonconventional methods, Thermal stress gradients

A B S T R A C T

Nonconventional methods have been used to obtain geothermal density data in regions without adequate holes need to make measurements or where detailed distribution values of this parameter are required. The method used in the present work uses data obtained from seismic tomography, velocity distribution of P waves and V_P/V_S ratio values, to define "warm" and "cold" regions in the crust. The distribution and intensity of radioactive heat sources near the surface is obtained using radiometric data from rocks. The heat flow at the surface of the Earth is obtained by addition of the heat generated by the sources studied with the heat flowing from deeper regions. With the method presented it is possible to obtain detailed maps of geothermal heat flow density at the Earth's surface. It is also possible to obtain the depth location of "warm" layers with fluids that can be used in several applications. Physical properties including radioactivity, thermal conductivity and heat expansion coefficient may be used to explain some earthquakes located near the contact zone of different geological materials.

1. INTRODUCTION

With the increased use of geothermal energy applications there is a need to use detailed maps of surface heat flow density values to identify anomalies of deep origin but also anomalies located near the Earth's surface. In the present work nonconventional methods are used with data obtained from seismic tomography and rock radioactivity data acquired from samples and/or radiometric charts. Other heat sources are not considered in this work. In addition to the heat flow density values, information about the existence of "cold regions" or "warm regions" and their location in depth is also provided.

Conventional methods of heat flow density measurements do not consider local heat sources. The analysis of the distribution of radioactivity shows the location of the boundary of the different formations obtained from geological maps and explain anomalies non detected by thermal conductivity values. The occurrence of some earthquakes near the contact zone of materials with different thermal properties may be explained by the occurrence of different thermal gradients normal to the contact surface with the formation of thermal stress gradients due to different thermal expansion coefficients experienced when heating or cooling processes occurs (Duque, 2023). This fact is used to explain earthquake occurrence near "Aldeia da Serra".

[1] Corresponding author: Maria Rosa Duque
Email: mrad@uevora.pt

Nomenclature

Q	geothermal heat flow
K	thermal conductivity of rocks
T	temperature
V_P/V_S	ratio between seismic velocities of P and S waves W
mW	milliwatt [10^{-3}W]
µW	microwatt [10^{-6}W]

2. THE METHOD USED

Geothermal heat flow density values at the surface of the Earth, Q_o, are interpreted as resulting from the addition of heat generated in the crust, Q_c, to the heat flowing from deeper regions, Q_M.

$$Q_o = Q_c + Q_M \tag{1}$$

Numerical models are made using crustal structure obtained by seismic tomography, considering heat transfer by conduction in the vertical direction (Duque, 2020). The Fourier conduction law is applied, the heat flow is obtained multiplying the thermal gradient value by the thermal conductivity of the formation traversed, and temperature values at different depths are obtained solving the equation

$$\frac{d^2\, T}{d\, Z^2} = -\frac{A}{K} \tag{2}$$

The thermal conductivity, K, and the heat production, A, have constant values in each layer.

2.1 Seismic data

V_P values and its distribution give information related with the number and thickness of the different layers in the crust. They are useful to identify anomalous layers, its dimensions and location in depth.

V_P/V_S values give information related with mechanical properties (Poisson ratio). High values of this parameter indicate regions with relatively low V_S values, with pores or fractures (Brantut & David, 2019). Pores or fractures in the crust are filled with water or gas whose thermal conductivity values are relatively law compared with thermal conductivity values of rocks, and the formation presents a low thermal conductivity value. This means that, for a specific Q value, if K decreases the grad T value must increase, and the region is described as a “warm region”. V_P/V_S values indicate regions with high V_S values without pores or fractures and presenting high values of thermal conductivity. Grad T values in these regions decrease and the region is described as a “cold region”.

2.2 Radiometric data

Different types of local heat sources may be found in the crust. They must be studied carefully taking into account the knowledge about the region studied. The main sources of heat in the crust are related to the radioactive decay of long-lived isotopes of uranium, thorium and potassium. The amount of these isotopes can be obtained in the laboratory using samples from the formations under study (Lamas et al., 2017) or through in-situ measurements. In our days it is possible to find radiometric charts of some regions that give us a detailed distribution of radiometric data (Duque, 2018; Batista et al., 2013).

3. APPLICATIONS

Heat flow density values have been obtained using the method described in some regions of Portugal mainland. Portugal mainland is located in the western part of the Iberian Peninsula in the northern hemisphere of planet Earth. It is surrounded by waters of the eastern side of the Atlantic Ocean in the western and southern borders of the country. Due to its location and tectonic history, the region has suffered different processes of compression and heating, being a very heterogeneous region with localized high heat flow density values in some (warm) regions and earthquakes occurring in another (cold) regions. Three different applications of the method are described. In the first, heat flow values were obtained in a region without boreholes needed to make conventional measurements of heat flow. In the second application a possible explanation for different values of heat flow measured in close boreholes is presented. The last application was made in a seismic active region without a possible explanation for those events. The application of the method to obtain the volume of a geothermal reservoir and the depth location of the bottom and lateral borders of the reservoir is also presented.

3.1 Beira’s region

The region studied is located in the central part of Portugal mainland, near the Portugal – Spain border, between latitude values of 39.8ºN and 41.0ºN and longitude values of 6.8º W and 7.7º W. The numerical method described was applied due to the non existence of boreholes (Duque, 2024) needed to make conventional heat flow density measurements.

The region is characterized by a very strong anomaly in the radiometric chart of mainland Portugal (Batista et al., 2013), occupying almost the entire area studied. The high values of radioactivity are associated to granites with different ages and different thickness. The heat production of the granites due to radioactive decay was obtained (Lamas et al., 2017; Miranda et al., 2015) and no other type of crustal heat sources was considered in the region. Ten heat flow density values were obtained using ten different models made for ten different points.

Seismic tomography (Veludo et al., 2017; Dundar et al., 2016) gives depth values of the Mohorovicic discontinuity considered as the depth of the crust in the region. The crust is formed by three different layers.

The "lower crust" is located just over the mantle and the velocity of P seismic waves present values between 6.5 to 6.7 or 6.8 Km s^{-1}. It is a region with very low heat sources (0.1 µW m^{-3}) and nearly constant thermal conductivity values (2.1 W K^{-1} m^{-1}). The "middle crust" is located between the "upper crust" and the "lower crust". The velocity of seismic P waves shows values between 6.1 and 6.5 Km/s and heat production values due to radioactive sources are 2.0 µW m^{-3}. The thermal conductivity values in this layer are around 2.5 W K^{-1} m^{-1}. A transitional layer was considered between the lower part of the "middle crust" and the upper part of the "lower crust" with heat production values of 1.35 µW m^{-3} and thermal conductivity of 2.3 WK^{-1} m^{-1}. The heat production in the upper crust is obtained from radioactivity data or measurements on samples from the region (Duque, 2018).

The heat flow density value of 35 mW m^{-2} was used of heat flow from greater depths. A value of 15ºC was used for surface temperature in the region. Table 1 shows the thickness of the different layers used in point 3 (Duque, 2020) and the heat production and the thermal conductivity value used in each layer. The value obtained for heat flow at the surface is 91 mW m^{-2} and the heat generated by thermal sources in the crust is 56 mW m^{-2}. This means that more than 61% of the heat flow obtained is originated by the heat sources in the upper crust.

Heat flow density values from 80 mW m^{-2} (minimum value found) to 99 mW m^{-2} (maximum value found) were obtained in the region (Duque, 2020). The differences between the heat flow values obtained are mainly due to the heat produced by crustal sources and the thickness of the layers where they are located. Heat sources in the crust generates heat flow values from 46 mW m^{-2} (minimum value) to 64 mW m^{-2} (maximum value). This means that 57.5 % to 64.6% of the geothermal heat flow at the surface has it source in the crust.

The heat flow density values found with this work shows a positive anomaly that was not obtained with the heat flow values measured to the west of this region.

Table 1. The model used to obtain the heat flow density value in point 3 (Duque, 2020).

Depth interval [Km]	Heat production [µW m^{-3}]	Thermal conductivity [W K^{-1} m^{-1}]
Surface-3	3.9	3.25
3-5	2.1	2.9
5-12	2.7	3.1
12-20	2.0	2.5
20-22	1.35	2.3
22-31	0.1	2.1

3.2 Different heat flow values measured in close regions

Two groups of heat flow density measurements obtained at similar latitudes, located to the west of the "Beiras region" and presenting very different values in close boreholes are presented in Table 2. No explanation was found for the differences obtained between measured thermal gradient values. Thermal conductivity data shows similar values in each group but with higher values in group 2.

Table 2. Location of the boreholes and heat flow density values measured.

Group	Longitude [º W]	Latitude [º N]	Q [mW m^{-2}]
1	7.749	40.169	60
1	7,756	40.155	59
1	7.754	40.148	74
2	8.094	40.163	85
2	8.064	40.155	59

Analyzing data from seismic tomography (Dundar et al., 2016) it is possible to see that crustal bottom depth is 32 Km for the two values of group 2, but a value of 30.5 Km is found for the first two values of group 1 and 31 Km for the last value of this group. The boreholes of group 1 seem to be located in different regions separated by a fault, or located in a region with inclined depth, making the connection between two different regions.

A detailed analysis of the geology (Meireles, 2024) of the region (Group 1) shows that lower values of heat flow were obtained in schist formations and some quartzite. The third borehole (group 1) is in a greywacke formation without quartzite. Greywacke is associated to higher values of radioactive heat production. Boreholes of group 2 are located to the west of group 1. Looking again to the geology of the region, a greywacke formation was found in one hole and a clay schist on the other.

The location of the points in the radiometric chart of rocks in mainland Portugal (Batista et al., 2013) shows that the three points of group 1 are associated to different values of radioactivity and heat production in the crust. The radiometric values is directly related with the heat flow values found. The second value of group 2 (last line) is in a local negative anomaly o radioactivity. The other value of the group is in a high -normal value for the region.

The higher values of heat flow are explained by high values of heat produced in the crust by radioactive sources. A possible addition of heat associated to a fault localized near the borehole may be considered but this fact was not verified.

3.3 Aldeia da Serra

Aldeia da Serra is a small village located in mainland Portugal near 38.8 º N latitude. This village became known due to the occurrence of small earthquakes in its vicinity.

Several local faults and geological contacts may be seen in geological maps (Carvalhosa & Leandro,1998; Zbyszewski et al., 1981), but, until know, no explanation was found in the specialized literature for the earthquake occurrences in the region. This work uses seismicity and seismic tomography data (Veludo et al., 2017) but introduces thermal properties in the analysis of the problem. Radiometric data were analysed to obtain information about heat sources due to radioactive decay (Batista et al., 2013). It is possible to see in Figure 1 earthquakes registered in the region during the year 2022. They are represented by black dots. The contacts between different geological formations are represented by solid black lines. Background colours in the figure are related with the radiometric content (Batista et al., 2013) of the formations. The lower values are represented by blue colour and the higher values by the brown colour.

The distribution of the earthquakes in the figure is not uniform. Analysing the figure, it is possible to see that to the west and northwest of Aldeia da Serra we have a group of earthquakes with no direct relationship with any fault. Geologically speaking the region is formed by granites with quartz and pegmatite intrusions. An intermediate value of radioactivity (green colours) is presented. The negative anomalies associated to the intrusions are not seen in the figure due to the configuration and small surface area of the intrusions. To the north and northeast of Aldeia da Serra there are granites again but without the intrusions. No earthquakes were detected in the region. The green colour indicates a similar value of radioactivity. To the east of Aldeia da Serra, a region with low values of radioactivity (blue colour) shows a few earthquakes near the external border. This anomaly seems to be related to a high content of quartz rock. It is a cold region with hard materials.

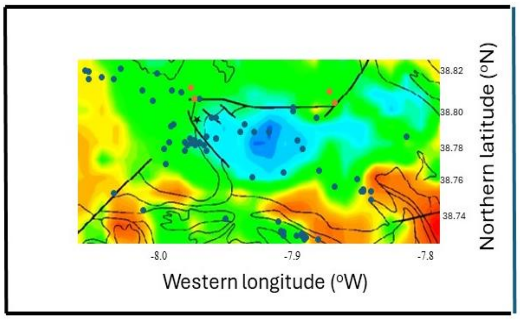

Figure 1. Location of earthquakes near Aldeia da Serra and radiometric information in background colors (partially adapted from Batista et al., 2013). The black star represents Aldeia da Serra location.

In the southern part of the figure, near longitude values of 7.9ºW and latitude values near 38.72ºN a new group of earthquakes is shown. This is a region formed by granites and diorites with high contents of quartz rock (tonalite). The earthquake location seems to be related with the contact zone between the two types of rock, in the green region.

The description presented suggest the earthquake occurrence in contact zones of quartz rock and granites. These two types of rock present different values for thermal conductivity (Zoth & Haenel, 1988), specific heat and radioactivity. Lower heat flow density values (low content of radioactive elements), low temperature values (high thermal conductivity) and low V_P/V_s values (hard rocks without pores/small fractures) forming "cold regions". Granites are characterized by higher content of radioactive elements and high values of temperature originating sometimes "warm regions". The formation of stress gradients of thermal origin near the contact zone of these materials can occur (Duque, 2023) with possible rupture of materials and earthquake occurrence. This kind of model is valid for earthquakes occurring in the first few kilometres from the surface.

Table 3 summarizes thermal properties studied making differences between rocks with high contents of quartz and granites. Temperature values in the contact zone must be the same in both types of rocks.

The depth and location of the earthquakes in the region is presented in Figure 2. Earthquakes located at latitude values near Aldeia da Serra are represented by orange dots (earthquake source between 8 and 12 Km depth). At latitude values lower than 38.76 º N, two groups of earthquakes are represented by blue dots representing earthquake depth values from 15 Km to 17 Km for earthquakes located at longitude values around 7.90º W and latitude values lower than 38.73º N and earthquake depth values from 15 Km to 21 Km at longitude values around 7.85 º W and latitude values from 38.74 to 38.76º N. Earthquakes with depth values from 14 to 17 km (dark green dots) were recorded in longitude around 8.0 º W values. Light blue dots represent earthquakes located between 2 and 3 Km depth.

Table 3. Thermal properties to be considered in the present study for two types of rocks.

High content of quartz rock	Granites
Low radioactivity values	Higher radioactivity values
High thermal conductivity	Lower thermal conductivity
Low temperature values	High temperature values
Formation of cold regions	Formation of warm regions

The vertical profile CC´ with an east-west direction, at a latitude of 38.75º N (Veludo et al., 2017) shows, at longitude values near 7.85º W, some perturbations in the depths of the seismic velocities of 6.4 Km s^{-1} and 6.3 Km s^{-1}. The ratio between V_P and V_S values shows a positive anomaly (V_P/ V_S > 7.5) in the upper part of the crust, from the surface to 10 Km depth, indicating a warm region with pores or fractures filled with water. No contrasts are shown, and no earthquakes were detected at the mentioned depths.

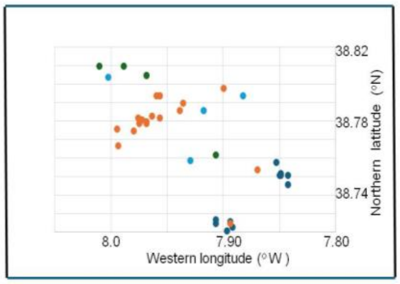

Figure 2. Location of earthquakes and depth of the earthquake source

At depths between velocity lines of 6.3 and 6.4 Km s^{-1}, from 15 Km to 21 Km depth, it is possible to see a "cold region" in the profile CC´, with low V_P/V_S values. The earthquakes are located near the upper and lower borders of the anomaly.

At latitude values lower than 38.73º N and in latitude interval from 38.77 to 38.80 º N no vertical seismic profiles are available (Veludo et al., 2017). The information on CC´ profile was complemented using horizontal distributions of P wave velocity and V_P/V_S ratio are also available at 1km, 4 km, 8 km, 12 km and 16 km depths (Veludo et al., 2017).

At longitude values near 8.0 º W, the velocity line of 6.3 Km $s^{-1}$is located at 19 Km depth ascending to 17 Km depth at longitude values near 7.9º W. The deformation of the velocity line 6.4 Km s^{-1} is more pronounced at 7.85 º W longitude. The material between the two velocities forms a deformed region that seems to be compressed by regional tectonic processes. Low values of V_P/V_S were found in the region with earthquakes from 17 Km to 19 Km depth. At depth intervals from 8 to 12 km, near longitude values of 8.0ºW, it is possible to see a vertical narrow strip forming a "warm region". Sharp contrast may be seen in the borders of the region that may be associated to earthquake occurrence.

Low values of V_P/V_S near the surface around Aldeia da Serra seems to be associated to quartz rock contents and crystal dimensions with earthquakes occurring near the contact region of quartz intrusions. Deep earthquakes in the region seems to be associated with compressed zones formed during tectonic processes in the region. At the surface, the cold regions seem to be associated to pure quartz rock found in intrusions or high quartz rock contents in different rocks found in the region. Aldeia da Serra is in a formation without appreciable quartz content and not affected by deep processes of deformation. No earthquakes were detected there.

3.4 The geothermal reservoir

Geothermal reservoirs may be found in rocks with pores or fractures filled by fluids, in the liquid or vapour phase or liquid + vapour mixture. There are also hot dry rocks reservoirs. To exploit these reservoirs, it is necessary to inject fluids from outside using boreholes made for that purpose.

The delimitation of the reservoir, particularly the bottom depth of the reservoir, is difficult to achieve using conventional methods of prospecting and sometimes involves drilling a large number of boreholes. It can be obtained, without major problems, from the analysis of the distribution of the ratio V_P/V_S values in the region. In regions with pores or fractures V_P/V_S values tend to be higher than those obtained in other regions. The fluid present in geothermal reservoirs presents very low values of thermal conductivity compared with thermal conductivity values from rocks without pores or fractures. The low thermal conductivity values originate the development of high thermal gradient values near the borders of the reservoir and an increase of temperature in the reservoir. With the location of the borders including the bottom depth of the reservoir is possible to obtain the volume of the reservoir and the amount of fluid for a known porosity. Using this data, it is possible to choose the applications to be carried out, taking into account the time interval required to replace the fluid in the reservoir.

4. SOME COMMENTS

The applications 3.1 and 3.2 show the importance of working with heat source values in the crust as well as the thickness of the different layers forming it. The application 3.2 highlights the need to consider heat sources near the surface when analyzing possible heat flow density anomalies. Data from group 1 were obtained in a transition zone between a region with high heat flow density values due to granites with high heat production values and high values of radioactivity and another region with heterogeneous distribution of radioactivity, sometimes with low values. Different values of heat flow density obtained in close boreholes is not necessarily an anomaly.

The application 3.3 shows how some problems usually considered as purely mechanical problems, may, sometimes, be analyzed and understood complementing the study with some thermal properties and thermal contrasts found in the region.

The last application solves a problem whose solution is necessary to project a possible application using geothermal energy. It can save time and money in the preparatory works of the application.

5. CONCLUSIONS

The method presented can be used to fill in heat flow density maps in regions without measured values or to obtain more detailed maps in regions with a few, but not enough number of measured data needed to understand heat flow distribution in the region.

It is possible to explain local heat flow anomalies combining local geological, thermal conductivity and heat sources data using V_P/V_S and radiometric data distribution in the region.

A detailed analysis of V_P/V_S values can give information about hidden contacts and mechanical and thermal properties contrast. That analysis can, sometimes, give information about the probability of earthquake occurrence near the borders of the contact region.

Geothermal reservoir location and volume can be detected using velocity variations of seismic waves. V_P/V_S values can give information related with fluid content and its temperature in the region.

Acknowledgement: Geological and radiometric data were obtained using GEOPORTAL OPEN DATA from LNEG. https://geoportal.lneg.pt/pt/dados_abertos/. Seismicity and earthquake depths were obtained from IPMA internet site. https://www.ipma.pt/pt/publicacoes/.

References:

Batista, M. J., Torres, L., Leote, J., Prazeres, C., Saraiva, J., & Carvalho, J. (2013). Carta Radiométrica de Portugal [Radiometric Chart of Mainland Portugal], Laboratório Nacional de Energia e Geologia (LNEG).

Brantut, N., & David, E. C. (2019). Influence of fluids on VP/VS ratio: increase or decrease?. *Geophysical Journal International*, *216*(3), 2037-2043. doi:10.1093/gji/ggy518.

Carvalhosa, A., Leandro, A. (1998). Carta Geológica de Portugal. Folha 36C- Arraiolos (escala 1:50 000) [Geological Chart of Portugal. Sheet 36C-Arraiolos (scale 1: 50 000)], Laboratório Nacional de Energia e Geologia (LNEG).

Dundar, S., Dias, N., Silveira, G., Kind, R., Vinnik, L., & Matias, L. (2016). Estimation of crustal bulk properties beneath Mainland Portugal from P wave tele-seismic receiver functions. *Pure and Applied Geophysics, 173,* 1949-1970. doi: 10.1007/s00024-016-1257-4.

Duque, M. R. (2024). Geothermal Heat Flow by Conduction in Mainland Portugal. *Inzynieria Mineralna,1,*1, 27-31. doi: 10.29227/IM-2024-01-03.

Duque, M. R. (2023). Problems associated with the contrast between thermal and mechanical properties of materials. *Brazilian Journal of Development, 9,* 3362-3370. doi: 10.34117/bjdv9n1-232.

Duque, M. R. (2020). Numerical Simulations of Terrestrial Heat Flow in Beiras Region, Mainland Portugal. *International Journal of Terrestrial Heat Flow and Applied Geothermics, 3,* 2-37. doi:10.31214/ijthfa.v3i1.48.

Duque, M. R. (2018). Heat Flow Density, Geotherms and Lithosphere Thickness in SW of Iberia (South of Portugal). *International Journal of Terrestrial Heat Flow and Applied Geothermics, 1,* 18-22. doi:10.31214/ijthfa.v1i1.9.

Duque, M. R. (2018). An attempt to obtain heat sources in the crust using non conventional methods. *Geophysical Research Abstracts, 20*, 9554.

Lamas, R., Miranda, M., Pereira, A., Neves, L., Ferreira, N., & Rodrigues, N. (2017). 3-D distribution of the radioelements in the granitic rocks of Northern and Central Portugal and geothermal implications. *Journal of Iberian Geology, 43,* 3-12. doi: 10.1007/s41513-017-0001-y.

Meireles, C. A. P. (2024). Folha 4 da Carta Geológica de Portugal (escala 1:200 000) [Sheet 4 of the Geological Chart of Portugal (scale 1:200 000), Laboratório Nacional de Energia e Geologia (LNEG).

Miranda, M., Lamas,R., Pereira, A., Ferreira, A., & Neves, L. (2015). Potencial térmico das rochas granitoides aflorantes na Zona Centro- Ibérica (Portugal) [Heat prodution of the granitic rocks outcropping in the Central Iberian Zona (Portugal)].*Comunicações Geológicas,102,* Especial I, 133-136.

Veludo, I., Dias, N., Fonseca, P. E., Matias, L., Carrilho, F., Haberland, C., & Villaseñor, A. (2017). Crustal seismic structure Beneath Portugal and Southern Galicia (western Iberia) and the role of Variscan inheritance. *Tectonophysics, 717,* 645-664. doi:10.1016/j.tecto.2017.08.018.

Zoth, G., & Haenel, R. (1988). Thermal conductivity, *Handbook of Terrestrial Heat-Flow Density Determinations, Appendix,* Kluwer Academic Publishers, 449-453.

Zbyszewski, G., Barros, A., Carvalhosa, A., & Ferreira, O. (1981). Carta Geológica de Portugal. Folha 36A- Pavia (escala 1:50 000) [Geological Chart of Portugal. Sheet 36A-Pavia (scale 1: 50 000)]. Laboratório Nacional de Energia e Geologia (LNEG).

Maria Rosa Duque
Universidade de Évora, Departamento de Física
Évora
Portugal Country
mrad@uevora.pt
ORCID 0000-0002-0350-9246