

Heat Flow Density Estimations in the Portuguese Northern Hercynian Massif using Silica Geothermometry

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ABSTRACT

Surface heat flow density (HFD) estimates in the Portuguese northern Hercynian Massif are difficult to obtain using the usual Fourier method. As a matter of fact, this zone is mostly composed by granitoid and metamorphic rocks, and most wells drilled there are too shallow for reliable HFD calculations; furthermore, HFD estimates are scarce and their geographical distribution is still very irregular. All these conditions imply that a HFD map for this region must be obtained using alternative methods, such as the silica geothermometry method.

Under certain conditions, the use of silica geothermometers to estimate HFD in mineral waters has proved to be an effective way to understand and establish the thermal regime in areas with scarce conventional HFD determinations. Because temperatures obtained with silica geothermometry are related to deep thermal conditions in the crust and to water-rock equilibrium, a regional HFD analysis may be carried out using those temperatures. The silica geothermometer, developed by Truesdell in 1976 (Truesdell, 1976), give good results for low SiO₂ concentrations, which is the case for the Portuguese northern Hercynian Massif, and is applied to more than 30 samples of mineral water occurrences reported for the zone. This number of samples, even though small, is considerably higher and more evenly distributed than conventional HFD estimates for the same area.

Application of silica geothermometry to northern Hercynian Massif waters shows a discrete reservoir temperature zoning, ranging from about 45 °C, in its southwest limit, to more than 120 °C, towards its northeast limit.

Using temperatures obtained by silica geothermometry and heat flow density values calculated through the conventional method in an area of 1° x 1° in the study zone, an empirical linear relationship between HFD and temperatures obtained by silica geothermometry is obtained and used to construct a HFD map for the Portuguese northern Hercynian Massif. The resulting HFD map is compared with the general geological and structural framework, and an attempt to a geothermal characterisation of the Portuguese northern Hercynian Massif is made.

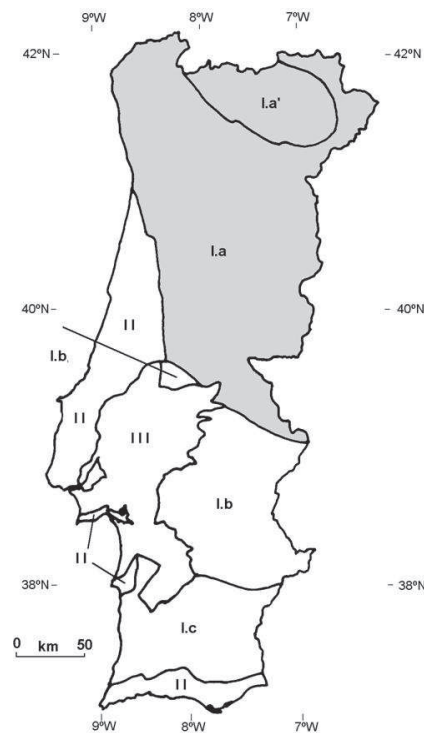


Figure 1. Structural units in Mainland Portugal. The Northern Hercynian Massif is highlighted (grey colour). I- Hercynian Massif. I.a- Centro-Iberian Zone; I.a'- Middle Galicia Sub-Zone; I.b- Ossa-Morena Zone; I.c- South-Portuguese Zone; II- Occidental and Meridional Meso-Cenozoic Borders; III- Tejo and Sado Tertiary Basins.

1. Introduction

Heat flow density mapping in Mainland Portugal is being updated since the early 80's. This is being done using the usual Fourier method, multiplying the calculated geothermal gradient in a borehole by the thermal conductivity of geological formations intersected by it. To update this map, a great deal of information has been gathered and studied. Most of the HFD information comes from southern Portugal, where intensive mining activity has favoured the existence of deep mining wells. However, in the northern areas of the Hercynian Massif there are only a few HFD estimates; following the experience of other authors (e.g., Swanberg and Morgan, 1979; Swanberg and Morgan, 1980; Prol-Ledesma and Juarez, 1986), the direct application of silica geothermometry may overcome this lack of information and applied to northern Portugal.

2. Geological Setting

The Hercynian Massif is a wide region 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 divided into several units (Figure 1) with different geological characteristics and ages. The Portuguese northern part of the massif is mostly composed by highly fractured granitoid rocks and schists; major fault systems are the NNE-SSW fracture system Régua-Verin-Penacova and the Vilarica fault (Ribeiro et al., 1979). These fault systems play an important role in the regional deep circulation of mineral waters. In fact, as shown in Figure 2, the regional trend of mineral water occurrences is related with those fault systems.

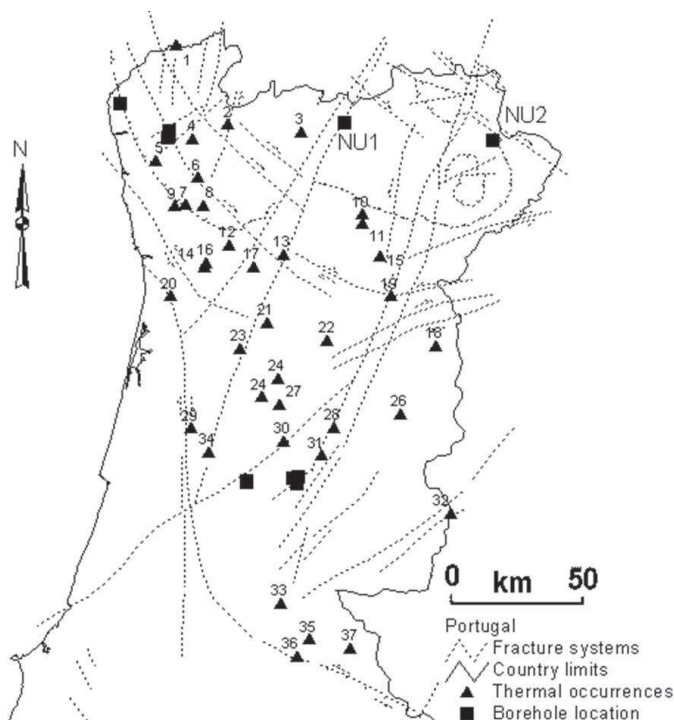


Figure 2. Location of mineral water occurrences and boreholes with HFD estimates in the Portuguese northern Hercynian Massif.

3. Methodology

In the Portuguese northern Hercynian Massif, under a shallow weathered zone with variable thickness, there is an intense fractured zone, beneath which unaltered rock is found. Here water flows through deep faults eventually reaching chemical water-rock equilibrium if their deep circulation time is long enough.

The geological characteristics of the Hercynian Massif make reliable HFD estimates difficult to obtain since most water wells only reach the shallow weathered zone. Furthermore, deep mining wells are scarce and irregularly distributed. These facts imply that only a small number of HFD estimates, using data from temperature measurements and thermal conductivity measurements in boreholes, is available. Since with such a few data it is not possible to obtain a reliable geothermal gradient that represents the geothermal conditions for the entire region, the use of silica (SiO_2)

Table 1. Identification and chemical characteristics of the thermal occurrences used in this study. N is the reference in Figure 2; Em. Temp. is the emergence temperature ($^{\circ}\text{C}$); Chem. Composition is the main chemical characteristics of the water; SiO_2 is the silica content (mg/l); and T_{SiO_2} is the temperature ($^{\circ}\text{C}$) obtained by the silica geothermometer developed by Truesdell (1976).

N	Name	EM. Temp.	Chem. Composition	SiO_2	T (SiO_2)
1	Caldas de Moncao	50	H ₂ S, HCO ₃ , Na, F	86	129
2	Caldas do Geres	47	HCO ₃ , Na, F, S ₂ O ₃	65	114
3	Carvalhelhos	22	HCO ₃ , Na, F	25	73
4	Caldelas	33	HCO ₃ , Ca, F	39	91
5	Quinta do Eirogo	25	H ₂ S, Cl, HCO ₃ , Na	59	110
6	Caldas das Taipas	32	H ₂ S, HCO ₃ , Na, F	35	87
7	S. Miguel das Aves	22	H ₂ S, HCO ₃ , Na	28	77
8	Caldas de Vizela	62	H ₂ S, HCO ₃ , Na, F	58	109
9	Caldinhas	30	H ₂ S, Cl, Na, F	86	129
10	Caldas do Carlao	29	H ₂ S, HCO ₃ , Na, F	60	111
11	São Lourenço	30	H ₂ S, HCO ₃ , Na, K	58	109
12	Caldas de Canavezes	30	H ₂ S, HCO ₃ , Na, F	41	93
13	Caldas de Moledo	45	H ₂ S, HCO ₃ , Na, F	34	84
14	Entre-os-Rios	19	H ₂ S, HCO ₃ , Na, F	43	95
15	Fonte Santa do Seixo	21	H ₂ S, HCO ₃ , Na	25	71
16	São Vicente	19	H ₂ S, HCO ₃ , Na, F	70	118
17	Caldas de Aregos	62	H ₂ S, HCO ₃ , Na, F	53	105
18	Fonte Sta de Almeida	19	H ₂ S, HCO ₃ , Na	37	89
19	Longroiva	34	H ₂ S, HCO ₃ , Na	68	116
20	Caldas de S. Jorge	23	H ₂ S, Cl, Na	56	107
21	Termas do Carvalhal	41	H ₂ S, HCO ₃ , Na, F	53	105
22	Caldas da Cavaca	28	H ₂ S, HCO ₃ , Na, F	54	105
23	S. Pedro do Sul	69	H ₂ S, HCO ₃ , Na, F	66	115
24	Banho de Alcafache	48	H ₂ S, HCO ₃ , Na, F	54	106
25	Caldas de Sangemil	50	H ₂ S, HCO ₃ , Na, F	82	126
26	Caldas do Cro	23	H ₂ S, HCO ₃ , Na	48	100
27	Felgueira	36	H ₂ S, HCO ₃ , Na, F	47	99
28	Caldas de Fonte Santa	48	H ₂ S, HCO ₃ , Na, F	33	83
29	Luso	27	SiO ₂ , Cl, Na, K	11	44
30	Caldas de S. Paulo	23	H ₂ S, HCO ₃ , Na	100	137
31	Unhais da Serra	37	H ₂ S, HCO ₃ , Na, F	48	100
32	Monfortinho	28	SiO ₂ , Cl, Na, K	18	60
33	Ladeira de Envendos	22	SiO ₂ , Cl, Na, K	11	41
34	Caldas de Penacova	19	SiO ₂ , Cl, Na, K	9	37
35	Fadagosa de Nisa	19	H ₂ S, HCO ₃ , Na, F	32	83
36	Monte da Pedra	20	H ₂ S, HCO ₃ , Na	30	80
37	Castelo de Vide	16	HCO ₃ , Na, Ca	16	55

geothermometers may be used to obtain further information about the regional thermal regime. With this in mind, and since the silica content of the mineral waters of the Portuguese northern Hercynian Massif is lower than 400 ppm (Prol-Ledesma and Juarez, 1986), the equation developed by Truesdell (1976) is applied:

$$T = \frac{1315}{5.205 - \log \text{SiO}_2} - 273.15 \quad (1)$$

where SiO_2 is the silica content in ppm. The equation is valid for situations where no steam losses occur, which is the case in the study area.

The relation between temperatures obtained through silica geothermometry (T_{SiO_2}) and heat flow density for each area can be empirically established, as is the case for the United States (Swanberg and Morgan, 1979):

$$T_{\text{SiO}_2} = m q + b \quad (2)$$

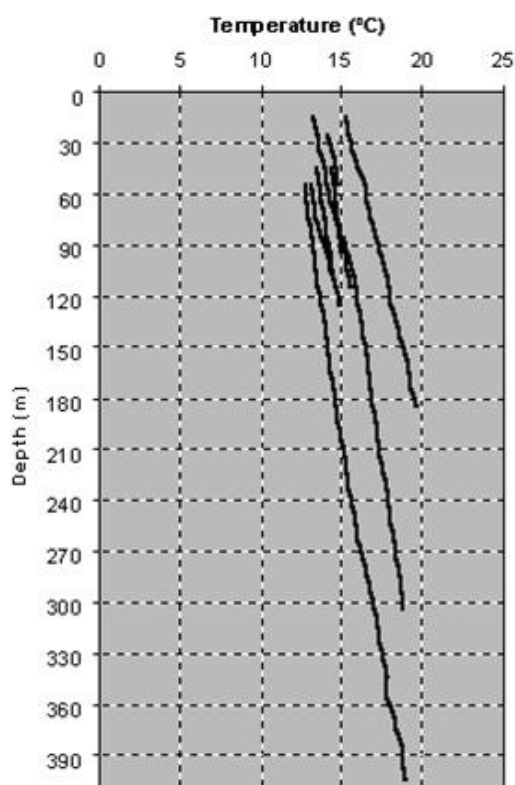


Figure 3. Temperature logs (Almeida, 1992; Duque et al., 1998) for the boreholes in the Portuguese northern Hercynian Massif shown in Figure 2.

4. The Portuguese Data

More than 30 samples from mineral water occurrences in the Portuguese northern Hercynian Massif with confirmed deep circulation due to their chemical characteristics or high emerging temperature are considered in this study (Table 1).

In chemical terms, most of these waters are low mineralised bi-carbonate sulphurous (Cruz et al., 1996). However, in the northeast region of the massif, there is a large number of occurrences with a significant CO_2 content which are not considered in this study because work carried out by Machado (1994) showed that the application of the silica geothermometer is not appropriate for this type of waters. The number of water samples used in this study, even though small, is considerably higher and more evenly distributed than conventional HFD estimations for the same region.

Heat flow density data used in this study are from temperature measurements made by Almeida (1992) and Duque et al. (1998) in boreholes located in the Portuguese northern Hercynian Massif (Figure 2) near some of the mineral water occurrences of Table 1. Figure 3 shows the temperature logs obtained in the boreholes of this study. In most of the boreholes no thermal conductivity measurements were made in cores or cuttings; so, for those boreholes where no thermal conductivity values are available, thermal conductivity values are from core samples from other boreholes in the same area (Almeida, 1993) or are taken from Cermak and Rybach (1982).

The wells have different depths and most of them are shallower than 120 m; however, for the purpose of this study, they are all considered to be deep enough to be in thermal equilibrium. Figure 4 shows the regression line of the temperature obtained through the use of silica geothermometers (TSiO_2) as a function of HFD. The regression yields the equation:

$$T_{\text{SiO}_2} = 0.647 q + 66.804 \quad (3)$$

with a correlation coefficient (R^2) equal to 0.4338. This coefficient compares estimated to actual y-values and ranges from 0 to 1. For the moment, the value of 0.4338 for the correlation coefficient that is obtained for Portuguese northern Hercynian Massif means that this HFD map based on silica geothermometry can only be considered as an indicator of the thermal regime of the region and so should be improved as more conventional HFD values are obtained. The high b value of Eq. (2) is a direct result of the small number of conventional HFD estimates; in this case, it is not possible to relate the value of b (66.8 °C) with the mean surface annual temperature, which, in northern Portugal, is about 14 °C.

5. Conclusions

The mapping of silica reservoir temperatures for the Portuguese Northern Hercynian Massif mineral water occurrences obtained with Eq. (3) (Figure 5, overleaf) shows a discrete reservoir temperature zoning, ranging from about 45 °C, in its southwest limit, to more than 120 °C, towards its northern limit. Most of the water-rock equilibrium temperatures range from 90 °C to 110 °C. On the other hand, occurrences near the western border of the Massif show low reservoir temperatures.

The HFD map for the Portuguese northern Hercynian Massif, calculated using the entire data set of HFD values for the north

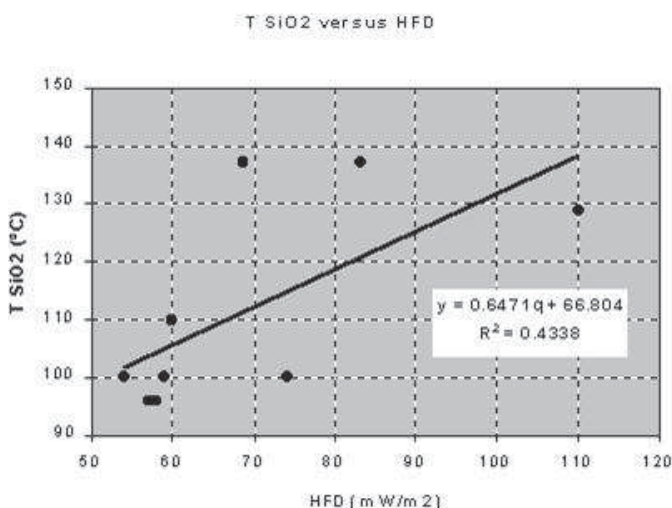


Figure 4. Silica temperature (°C) as a function of HFD (mW/m^2) for mineral waters in the Portuguese northern Hercynian Massif of HFD (mW/m^2) in selected wells.

where m and b are related with water circulation depth and surface average annual temperature, respectively, and q is heat flow density in mW/m^2 . For the United States the parameters m and b were determined through statistical analysis of more than 100,000 samples: for some geothermal provinces $m=670\text{m}^2\text{W}^{-1}$ and $b=13.2^\circ\text{C}$ and to regions of $1^\circ\times 1^\circ$ size, $m=680\text{m}^2\text{W}^{-1}$ and $b=12.4^\circ\text{C}$ (Swanberg and Morgan, 1980).

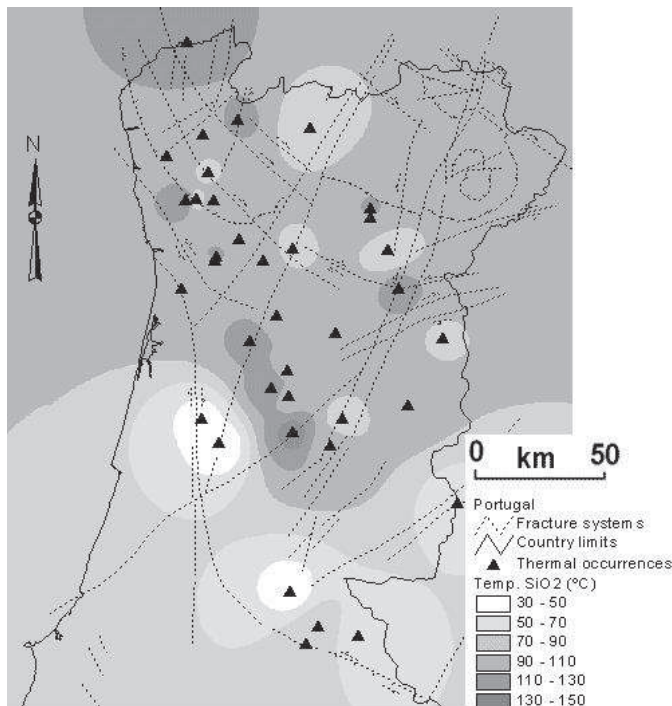


Figure 5. Reservoir temperatures (°C) obtained through the application of the silica geothermometer (Truesdell, 1976) to the selected mineral occurrences of this study.

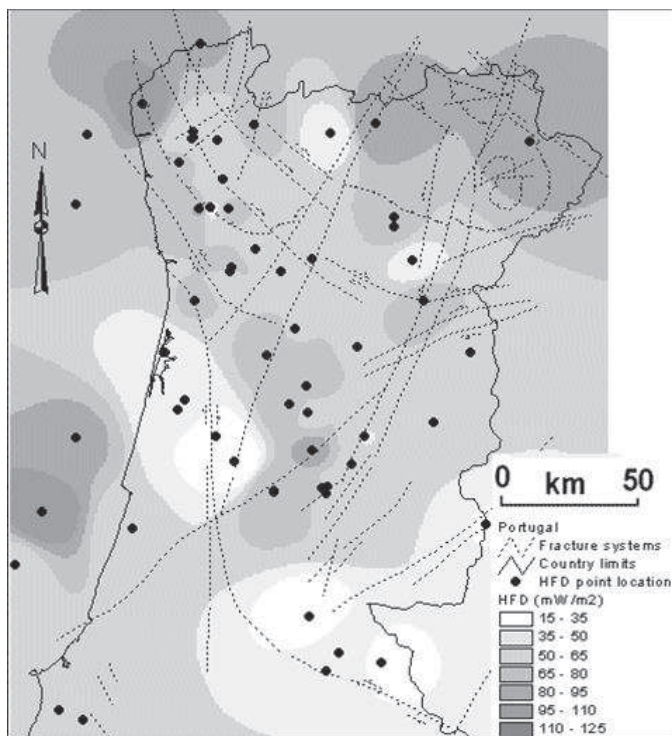


Figure 6. Heat flow density map for Portuguese northern Hercynian Massif. To construct this map, HFD data from Southern Portugal and the West Meso-Cenozoic Border were also used to constrain the northern Hercynian Massif values.

part of Portugal (Figure 6), indicates that HFD values for this area range from 65 to 80 mW/m². In the northern part of the Massif, however, there is a HFD increase. This result agrees with the results reported by Fernandèz et al. (1998).

6. Final Comments

Heat flow density estimates by silica geothermometry appears to be a good approach to complement conventional HFD estimates. However, the HFD map for the Portuguese northern Hercynian Massif must be updated as more HFD in boreholes are obtained. So, at this stage, due to the small number of HFD estimates in boreholes for the region of the study, the silica geothermometry method must be used with caution and be considered only as an indicator of the regional thermal regime.

References

- Almeida, L.C., 1992. Prospecção geotérmica - Determinação de gradientes geotérmicos em furos de sonda. Boletim Informativo do INMG.
- Almeida, L.C., 1993. Prospecção geotérmica - Cálculo de condutividades térmicas em amostras de rochas. Boletim Informativo do INMG. 7p.
- V. Cermak, and Rybach, L., 1982. Thermal conductivity and specific heat of minerals and rock. In: G. Angenheister (Editor), Landolt-Bornstein Numerical Data and Functional Relationships in Science and Technology. New Series, Group V, 16, Springer-Verlag, Berlin.
- J. F. Cruz, Lourenço, M. C., Rodrigues da Silva, A. M., Ramalho, E. C. e Correia, A., 1996. Breve caracterização das ocorrências termais com temperatura superior a 20°C em Portugal Continental, Boletim de Minas, 33 (2), 129-137.
- M. R. Duque, Santos, F. M. and Mendes Victor, L., 1998. Heat Flow and deep temperatures in the Chaves Geothermal System, Northern Portugal. Geothermics, 27, 1, 75-87.
- M. Fernandèz, Marzán, I., Correia, A. and Ramalho, E. C., 1998. Heat flow and lithospheric regime in the Iberian Peninsula. Tectonophysics, 291, 29-53.
- M.J.C. Machado, 1994. Aplicabilidade dos geotermómetros químicos na determinação da temperatura dos reservatórios das águas gasocarbónicas. Estudos, Notas e Trabalhos do IGM, 36, 43-52.
- R.M. Prol-Ledesma, and Juarez, G., 1986. Geothermal Map of Mexico. Journal of Volcanology and Geothermal Research. 28, 351-362.
- A. Ribeiro, Antunes, M. T., Ferreira, M. P., Rocha, R. B., Soares, A. F., Zbyzewsky, G. Moitinho de Almeida, F. Carvalho, D. and Monteiro, J. H., 1979. Introduction à la Géologie Générale du Portugal, Serviços Geológicos de Portugal, Lisboa, Portugal, 113p.
- C.H. Swanberg, and Morgan, P., 1979. The linear relation between temperatures based on the silica content of groundwater and regional heat flow: a new heat flow map of the United States. Pure Applied Geophysics, 117, 227-241.
- C.H. Swanberg, and Morgan, P., 1980. The silica heat flow interpretation technique: assumptions and applications. J. Geoph. Research, 85, 7206-7214.
- A.H. Truesdell, 1976. Summary of section III, Geochemical Techniques in exploration. Proceedings of the 2nd U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, Calif. VI, 53-79.