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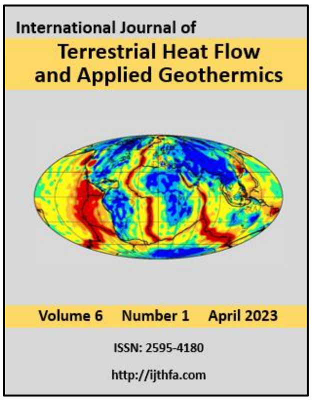

Geothermal Resources of European Continent: A Regional Assessment

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Abstract

A regional assessment of geothermal resources of the continental region of Europe is attempted in the present work. It is based on results of observational data on heat transfer by conduction as well as hydrothermal and magmatic processes in the upper crust and makes use of geothermal data reported at the website of IHFC and also estimates based on available information on occurrences thermal springs and volcanic events. The resource assessment has been carried out for 8109 sites distributed in 39 countries. These datasets were reevaluated and spatially gridded using kigrid interpolation to construction of regional distribution maps of geothermal resources and interpreted on the basis of available information on tectonic setting and geological characteristics. The estimates for volcanic areas are based on a modified method of magmatic heat budget (MHB). has been employed in deriving estimates of geothermal resources in areas of recent volcanic activity. According to results obtained the total resource base (RB) at 6km on depth is estimated to be 8.653.306 ± 7 GJ. The mean resource base per unit area (RBUA) is ~ 985 GJ. The prominent features in geothermal maps are the presence of localities with significantly high values of resource base greater than 2000 GJ in countries such as Russia, Italy, Iceland, and west Norway. In addition, vertical distributions of temperatures were calculated in for depths reaching down to 6 km. The results obtained indicate potential availability of high temperature resources in vast regions of the European continent.

1. Introduction

Europe is recognized as one of the largest of world's continents, covering a large percent of the Earth's land area, according to the United Nations (UN), the European continent is made up of 50 countries (plus Kosovo that is a partially recognized state in southeast Europe and was declared its independence from Serbia in 2008). Europe is 10.530.751 km² in size and has a population of around 747 million inhabitants, on the southern side, it is bordered by the African continent and on the northern side by Arctic regions. Along the eastern and southern sides are regions of the Atlantic Ocean. Most geographers define land area of Europe as the land mass falling between latitudes of 35 and 90 degrees north and west longitude of 20 degrees and east longitude of 40 degrees. The western border of this continent is often considered as the Atlantic. According to physiographic characteristics there are five major regions, classified as: eastern, northern, central, southern, and western. The map of Figure (1) illustrates this geographic setting.

Figure 1 – Geographic setting and country outlines of the European continent, with illustration of physiographic characteristics.

The **eastern** segment of **Europe** is a region that has several interpretations, often contradictory and influenced by geopolitical and ideological factors. The number of eastern European countries depends on the area included in each interpretation. Even so, even if they do not have any absolute homogeneity, most of the countries in the region have several similarities such as the strong presence of Slavic languages and the Orthodox Christian religion. In addition, most of these (with the exception of Greece) adopted at some point in their histories the socialist economic regime and the one-party political regime, almost all between the years 1945 and 1989.

The **Northern** sector encompass Norway and Sweden, located on the Scandinavian Peninsula. In addition to Finland, Iceland and Denmark; it also covers Estonia, Latvia and Lithuania, which from 1990 became independent from the then Soviet Union. The inclusion of these countries in the region is justified by economic reasons and by their ethnic and cultural proximity to the Finns.

Central region is the set of countries in Europe with most of its territory connected to the Alpine ranges, including its extensions to the Balkans and the Carpathians. These countries or their ancestors were historically in the situation of being alternately invaded and sometimes administered by western European countries (notably the Holy Roman Empire), Russia, Poland-Lithuania and even the Byzantine Empire.

The region is further subdivided into two groups of countries: The Alpine countries include Germany, Austria, Slovenia, Liechtenstein and Switzerland. The Visegrád Group, also called V4: Hungary, Poland, Czechia and Slovakia.

The **Southern region** also called as the Mediterranean, comprises the countries located in the south of the continent, almost all bathed by the Mediterranean Sea: Italy, Greece and European Turkey, in addition to several microstates - Vatican, San Marino, Monaco, Malta and Andorra. Portugal and Spain are incorporate in western region.

The **Western region** that covers some of the so-called Atlantic countries, that is, bordering the Atlantic Ocean (United Kingdom, Republic of Ireland and France); those that maintain a direct relationship with the Atlantic through the North Sea: the Netherlands, Belgium and Germany; and landlocked countries that are directly or indirectly linked to the west (Austria, Switzerland, Luxembourg and Liechtenstein).

2. Estimates of Heat Flow

Models of subsurface temperatures derived from one-dimensional and finite-element, finite-difference modelling are especially sensitive to input heat-flow values. Reliability in assessment of a representative surface heat flow or regional heat flow requires firstly an assessment of the quality of the available data and secondly a subjective analysis of the high-quality data to identify heat flow components required for a particular model.

In the case of unidimensional variation of temperatures, the heat flow (Q) is determined as the product of the temperature gradient (Γ) and the conductivity thermal (λ):

$$Q = \Gamma . \lambda \pm \sigma_Q \qquad (1)$$

Where the standard deviation (σ_Q) in heat flow determination is given by:

$$\sigma_Q = \sqrt{\left(\frac{\partial Q}{\partial \Gamma}\right)^2 \sigma_\Gamma{}^2 + \left(\frac{\partial Q}{\partial \lambda}\right)^2 \sigma_\lambda{}^2} \qquad (2)$$

Where σ_Γ and σ_λ are the standard deviation by geothermal gradient and thermal conductivity respective.

3. Procedures adopted for Assessment of Geothermal Resources

The terms resource and resource base (RB) used in this work refer to geothermal energy. The geothermal resource base calculations in the present work were carried out following the methodology proposed in earlier studies (see for example: Muffler and Cataldi (1978), Battocletti (1999), Huttrer (2001), Barbier (2002), Cardoso et al. (2010)). Volumetric method (White and Williams, 1975) or "stored heat" (Bolton, 1973) was considered adequate for this purpose.

In the terminology proposed by Muffler and Cataldi (1978) the resource base (RB) is the excess thermal energy up to a specified depth. In gridded data sets the resource base (Q_{RBi}) for the i^{th} cell, of thickness *di*, associated with its temperature distribution, is given by the relation:

$$Q_{RBi} = \rho_i \, C_{pi} \, A_i \, d_i \left(T_i - T_{0i}\right) \qquad (3)$$

where ρ_i is the average density, c_{pi} the specific heat, A_i the area of the cell, T_i the bottom temperature and T_{0i} upper surface temperature.

At this point, it is clear that we need to come up with a procedure for assessment of regional geothermal resources. Vieira and Hamza (2019) proposed use of resource base per unit area (RBUA) as a better indicator of the large-scale distribution of resources. The relation between heat flow and RBUA can be examined using standard statistical techniques.

Similar previous studies used this methodology Hamza et al. (2020), Gomes et al. (2021) and Hamza et al. (2022).

4. Summary of Heat Flow Data

A number of geothermal studies have been carried out in the regions of Europe. These include heat flow measurements, studies of thermal spring systems and assessment of geothermal resources. The data sets used in this work was been compiled of Global Heat Flow Database (GHFD) maintained by the International Heat Flow Commission (IHFC) of the IASPEI. It includes results of measurements in both land and adjacent marine sites.

The database used was adjusted to include only values greater than 25 mW/m^2, which allowed for the elimination of over- or under-estimated data. According to Cermak, 1979 this is the average minimum value of heat flux for different regions of Europe. The data density is relatively high in the western segment. A summary of data reported in these compilations is presented in Table (1). It includes the name of region, respective number (N) of data within that region and the mean heat flow (Q) in mW/m^2.

As can be noted by the statistics of Table (1) most of the measurement sites are located in the eastern parts of the continent. In this table, the data are subdivided into land and marine types. The Figure (3) illustrate the heat flow map of Europe.

Table 1 – Summary of geothermal data compiled for main regions of Europe.

Region	N	Q mean
Eastern	3649	53.9 ± 0.3
Northern	490	48 ± 2
Central	1204	72.0 ± 0.6
Western	1867	77.4 ± 0.5
Southern	899	66 ± 2
Total	***8109***	***64 ± 2***

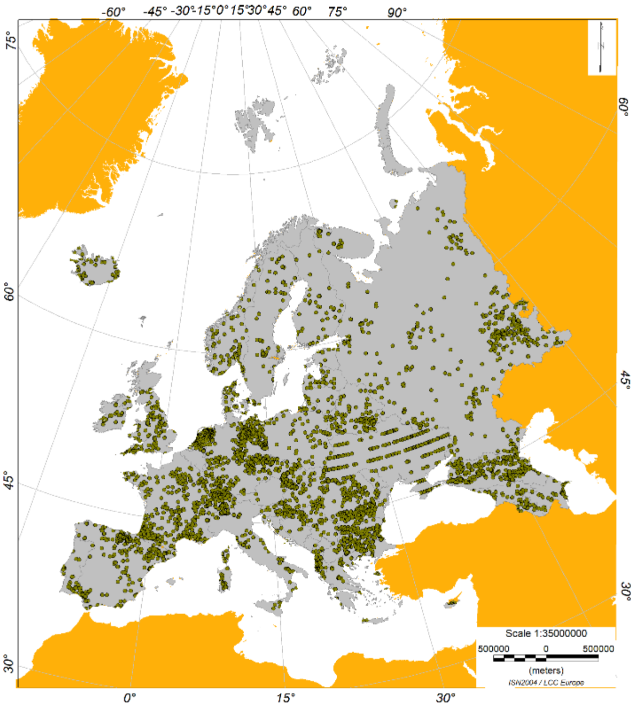

Figure 2 – Distribution Global Heat Flow Database (green dots) in Europe used in this work.

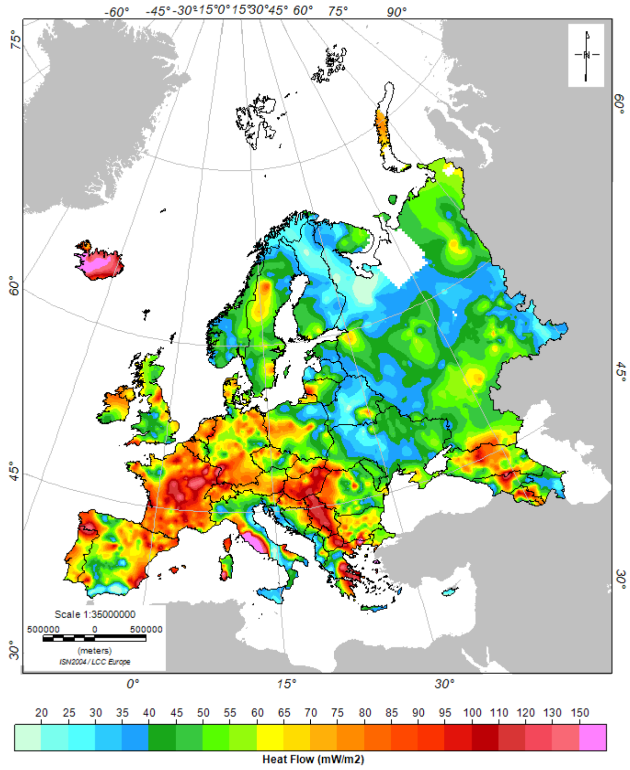

Figure 3 – Heat flow map of Europe.

Generally, the heat flow decreases from the younger to the older tectonic units and the units of the same tectonic history usually display similar heat flow values. With the knowledge of the age of the latest tectono-thermal event, the characteristic surface geothermal activity can be predicted (Hamza and Verma, 1969).

For the construction of the distribution grids to geothermal maps, we used the Kigrid interpolation in the software Oasis Montaj (Seequent) and geographic projection ISN2004/LCC Europe. Note that the data density is relatively high in the western segment relative to the eastern parts.

5. Results of Regional Geothermal Resources Assessments

In this item, the regions for resources assessment ae organized by regions as cited. Hence only selected data sets (complete with values of essential parameters employed for resources assessments) are employed in deriving estimates reported in data tables.

5a. Eastern Europe

Eastern Europe is a sub region of the European continent. As a largely ambiguous term, it has a wide range of geopolitical, geographical, ethnic, cultural, and socio-economic connotations. The vast majority of the region is covered by Russia, which spans roughly 40% of the continent's landmass while accounting for approximately 15% of its total population. Resource assessments were carried out for 7 countries in Eastern Europe. Details of the assessments are given in Table (2) where N is geothermal data number. The geothermal resources base distribution in the eastern Europe is illustrated in Figure (4).

Table 2 – Summary of resources base data (RB and RBUA) in Eastern Europe.

Region	Area (km^2)	N	RB (10^{21} J)		RBUA (GJ)
			TOTAL	STD	
Armenia	29743	52	35,1	0,3	61.357
Azerbaijan	86.600	261	66,6	0,1	200.596
Belarus	207.600	185	142,0	0,3	126.170
Georgia	69.700	46	36,2	0,3	23.876
Moldavia	33.846	14	36,9	0,4	5.165
Russia	17.100.000	2348	176.807	42,9	2.427.735
Ukraine	603.700	743	576,2	0,3	709.186
Subtotal		**3649**			**3.554.085**

5b. Northern Europe

A restrictive definition may describe the Northern Europe as being roughly north of the southern coast of the Baltic Sea, which is about 54^0N (latitude), or may be based on other geographical factors such as climate and ecology. Resource assessments were carried out for five countries in northern Europe. Details of the assessments are given in Table (3) where *N* is geothermal data number. In some countries, surface areas listed are actually areas above sea level. The data distribution is illustrated in Figure (5).

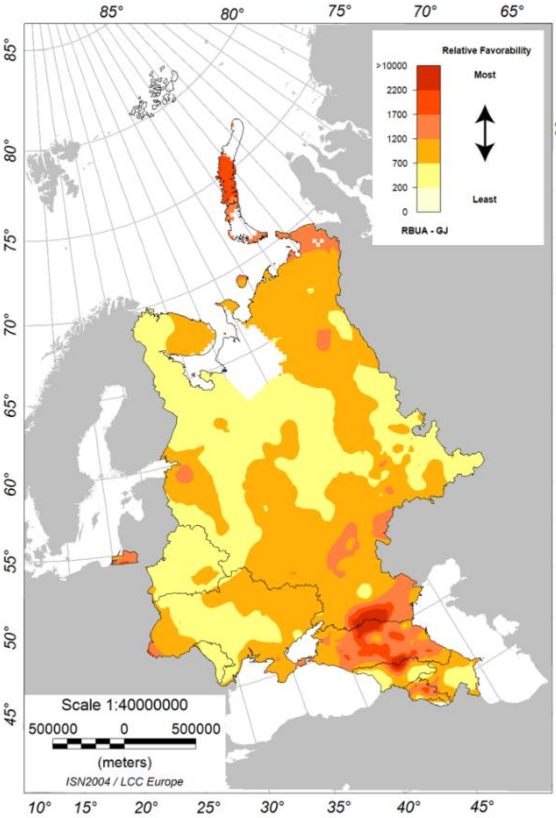

Figure 4 – Distribution of geothermal resource base per unit area (RBUA) in the Eastern Europe.

Table 3 – Summary of resources base data (RB and RBUA) in the Northern Europe. N refers to number of geothermal data number.

Region	Area (km^2)	N	RB (10^{21} J)		RBUA (GJ)
			TOTAL	STD	
Denmark	42.951	64	41.0	0.1	61.156
Finland	388.440	128	159.0	0.5	60.026
Iceland	103.000	70	305.4	1.8	207.526
Norway	385.207	103	534,8	2.8	146.017
Sweden	528.447	125	286	0.5	67.597
Subtotal		***490***	---	----	***542.322***

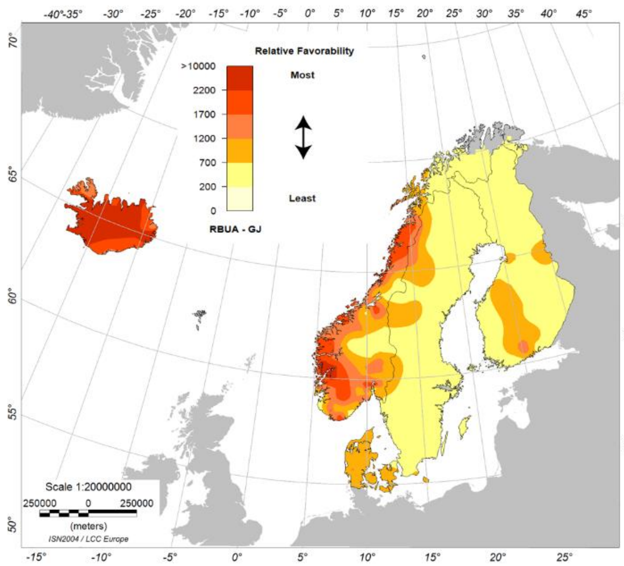

Figure 5 – Distribution of geothermal resource base per unit area (RBUA) for the Northern region of Europe.

5c. Western Europe

Southern Europe is focused on the three peninsulas located in the extreme south of the European continent. These are the Iberian Peninsula, the Apennine Peninsula, and the Balkan Peninsula. Resource assessments were carried out for 6 countries in western Europe. The geothermal data of Andorra, Belgium, Luxembourg, and Monaco are inaccessible. Details of the assessments are given in Table (4) where *N* is geothermal data number. In some countries, surface areas listed are actually areas above sea level. The data distribution of geothermal resources is illustrated in the map of Figure (6).

Table 4 – Summary of resources base data (RB and RBUA) in the Western Europe.

Region	Area (km^2)	N	RB (10^{21} J)		RBUA (GJ)
			TOTAL	STD	
Andorra	467	--	--	--	--
Belgium	30.688	--	--	--	--
France	551.695	575	592,3	0,4	617.370
Ireland	70.273	24	57,9	0,5	19.781
Luxembourg	2.586	--	--	--	--
Monaco	2	--	--	--	--
Netherlands	41.850	463	47,9	0,02	530.075
Portugal	92.212	76	114,9	0,6	94.674
Spain	505.990	389	475,5	0,6	365.574
United King.	243.610	340	369,3	0,5	515.447
Subtotal		***1867***	--	--	***2.142.921***

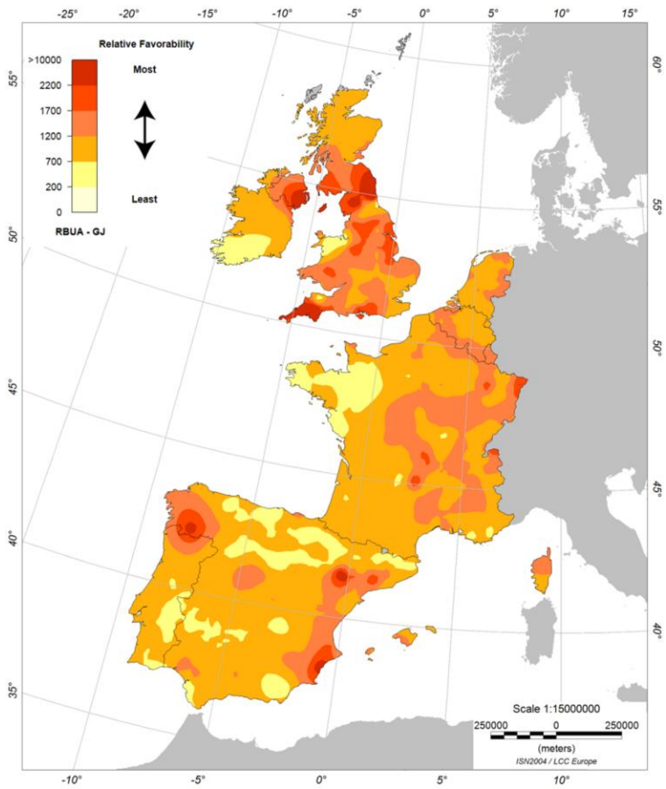

Figure 6 – Distribution of geothermal resource base per unit area (RBUA) in the Western Europe.

5d. Central Europe

Localized between western and eastern Europe the central Europe comprises most of the former territories of the Holy Roman Empire and hose of the two neighboring kingdoms: Poland and Hungary. Resource assessments were carried out for 10 countries in central Europe, Liechtenstein do not have geothermal data accessible. Details of the assessments are given in Table (5), where N is geothermal data number. In some countries, surface areas listed are actually areas above sea level.

The distribution of geothermal resource base per unit area (RBUA) for countries in central Europe is illustrated in the map of Figure (7).

Table 5 – Summary of resources base data (RB and RBUA) in the Central Europe.

Region	Area (km^2)	N	RB (10^{21} J)		RBUA (GJ)
			TOTAL	STD	
Austria	83.871	24	91,2	0,6	26.098
Czech Rep.	78.867	167	73,9	0,1	155.325
Estonia	45.228	10	34,5	1,0	7.601
Germany	357.588	623	379,0	0,2	665.098
Hungary	93.025	39	142,0	0,9	59.670
Latvia	64.589	31	51,0	0,5	24.500
Liechtenstein	158	--	--	--	--
Lithuania	65.300	10	63,5	3,4	1.490
Poland	322.575	54	257,3	1,4	43.074
Slovakia	49.035	79	54,6	0,2	100.168
Switzerland	41.285	167	81,9	0,2	331.173
Subtotal		***1204***	--	--	***1.414.197***

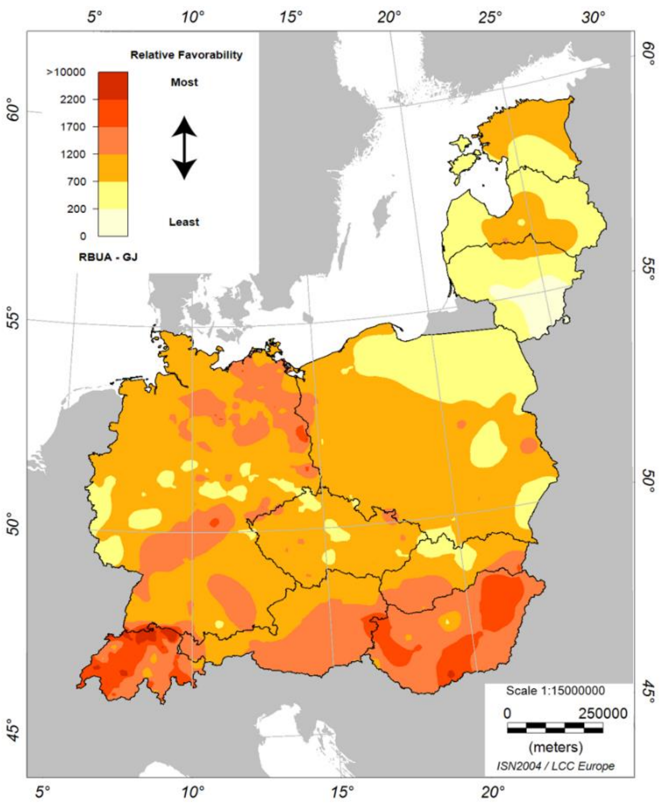

Figure 7 – Distribution of geothermal resource base per unit area (RBUA) for countries in Central Europe.

5d. Southern Europe

Southern Europe is focused on the three peninsulas located in the extreme south of the European continent: Iberian Peninsula, Apennine Peninsula, and Balkan Peninsula. Resource assessments were carried out for 11 countries in southern Europe that have accessible geothermal data. Details of the assessments are given in Table (6), where N is geothermal data number.

The data of resources base distribution in southern region of Europe is illustrated in the map of Figure (8).

Table 6 – Summary of resources base data (RB and RBUA) in the Southern Europe.

Region	Area (km^2)	N	RB (10^{21} J)		RBUA (GJ)
			TOTAL	STD	
Albania	27.748	62	16,9	0,3	37.845
Bosnia &Her.	51.197	13	59,3	1,1	15.047
Bulgaria	110.994	245	116,0	0,2	257.144
Croatia	56.594	76	54,6	0,3	73.328
Cyprus	9.251	10	6,5	0,1	6.988
Greece	131.957	83	143,0	1,5	90.259
Kosovo	10.887	--	--	--	--
Italy	302.073	104	567,6	7,8	195.421
Macedonia	25.713	10	33,5	1,1	13.016
Malta	316	--	--	--	--
Montenegro	13.812	--			--
Romania	238.397	256	240,7	0,3	258.016
San Marino	61	--	----		--
Serbia	88.499	24	137,1	1,0	37.169
Slovenia	20.273	16	23,5	0,8	18.549
Turkey	783.562	--	--	--	--
Vatican	0.44	--	--	--	--
Subtotal		***899***	--	--	***1.002.782***

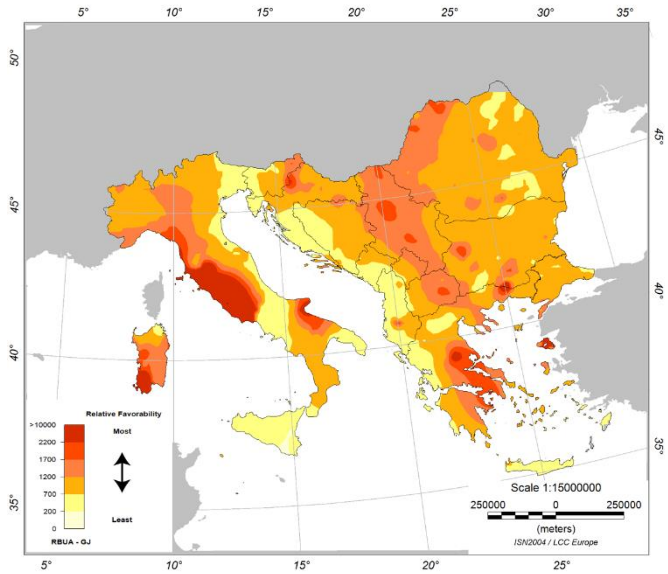

Figure 8 – Distribution of geothermal resource base per unit area (RBUA) for countries in Southern Europe.

6. Integrated Resource Base for Europe

A reappraisal of geothermal data of the mainland of Europe has been carried out based on data sets available at the IHFC website. The current compilation makes use of geothermal data reported at the website of IHFC but also estimates based on available information on occurrences thermal springs and volcanic events.

The resource assessment has been carried out for 8109 sites distributed in 39 countries (11 countries in the Europe do not have geothermal data disponible).

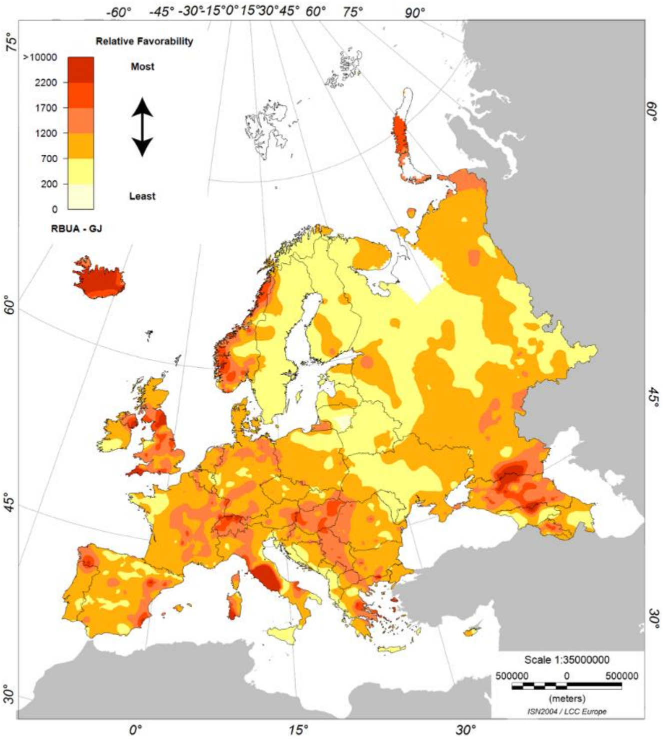

Figure 9 – Integrated resource base per unit area (RBUA) in the Europe Continent.

7. Crustal Temperatures

When the temperature condition at the depth cannot be tested directly, the temperature at the part exceeding the drilling depth can be inferred by indirect methods. Improved estimates of the temperature variation within the crust can be obtained using the relationship proposed by Hamza (1982) and Alexandrino (2008), which considers the lateral thermal variations of the medium and the temperature variation as a decreasing factor as one increases. extends deeper into the crust (α).

Thus, the parameter u, introduced as the variation of this factor with the temperature inside the analyzed well, is given as:

$$u = 1 + \alpha . T_z \quad (4)$$

The relation to temperature variation in depth (Tz) by heat flow measure in surface (q) is obtenaid:

$$T_z = \frac{1}{\alpha}\left\{(1+\alpha T_0)\left(e^{\left[\left(\frac{\alpha}{\lambda_m}\right)\left(q_z - A.D.z + A.D^2\left(1-e^{-\left(\frac{z}{D}\right)}\right)\right)\right]} - 1\right)\right\} \quad (5)$$

The Figure (10) illustrated the temperature variation at 6km depth in France. Note that the largest 6km temperature distribution calculated in the country varies from the range of 150-250ºC.

One of the convenient means of illustrating vertical distribution of excess temperatures is by using stacks of crustal temperature maps at conveniently chosen depth levels, which allow a sequential depth perspective. These datasets were reevaluated and spatially gridded using kigrid interpolation to construction of regional distribution maps of geothermal resources and interpreted on the basis of available information on tectonic setting and geological characteristics.

Results of such an attempt to 3-6 km on depth is illustrated in Figure (11), where it is possible to identify areas with temperature in this depth.

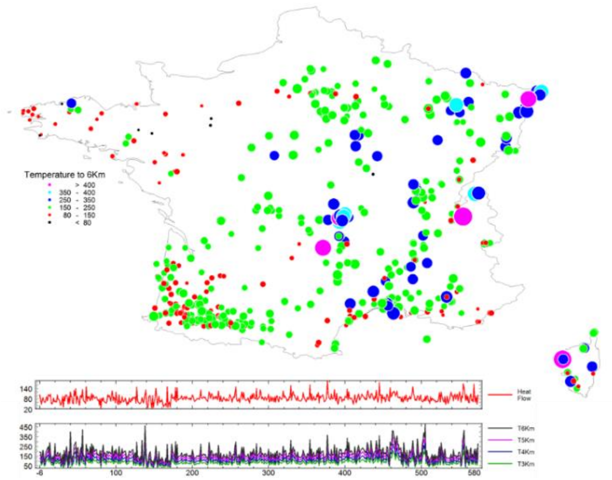

Figure 10 – Temperature distribution in the 6km depth in the France.

8. Conclusions

A modified method of magmatic heat budget (MHB) has been employed in deriving estimates of geothermal resources in areas of recent volcanic activity. These datasets were reevaluated and spatially gridded using kigrid interpolation to construction of regional distribution maps of geothermal resources and interpreted on the basis of available information on tectonic setting and geological characteristics. According to results obtained the total resource base (RB) at 6km is estimated to be 8.653.306 ± 7 GJ. The mean resource base per unit area (RBUA) is 984,96 GJ.

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The first author of this work held the position as Full Professor in Geophysics (before his retirement) of the National Observatory, Rio de Janeiro. The second author is Coordinator of the Department of Geophysics of the National Observatory (ON/MCTI) at Rio de Janeiro. The fourth author is professor at the Institute of Science Engineering and Technology, of the Federal University of Jequitinhonha and Mucuri Valleys, Teófilo Otoni, Brazil.

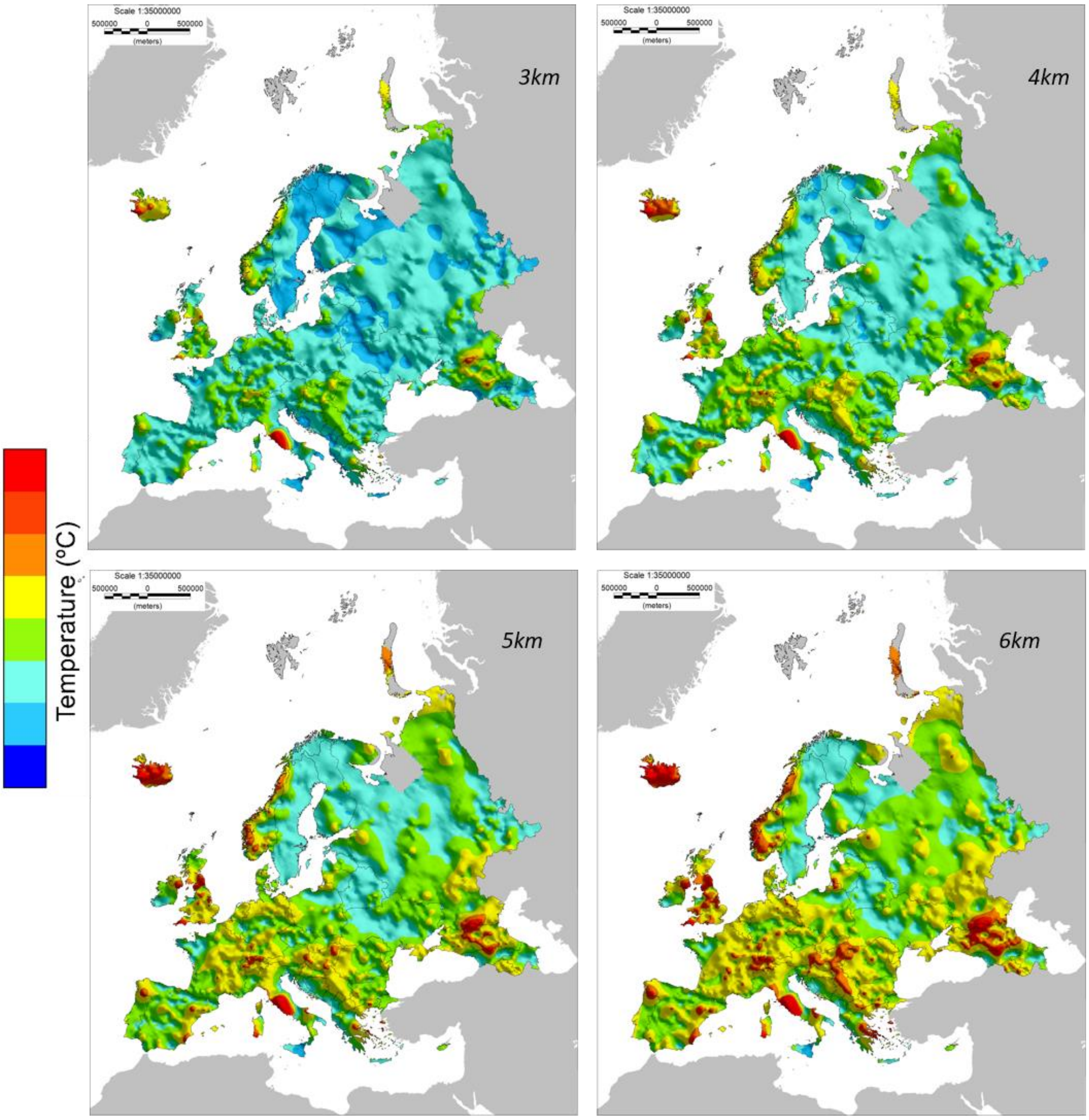

Figure 11 – Crustal temperature distribution in the 3-6km depth in Europe.

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