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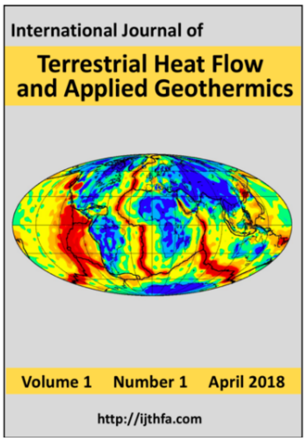

Deep-seated Geothermal Resources of the Parana Basin

Antonio Jorge de Lima Gomes[1], Jorge Luiz dos Santos Gomes[1,2]

[1]Institute of Science Engineering and Technology, Universidade Federal dos Vales do Jequitinhonha e Mucuri, Teófilo Otoni, Brazil.
[2] Department of Geophysics, National Observatory, Rio de Janeiro, Brazil.

Email address
antonio.gomes.br@gmail.com (A.J.L. Gomes)
Corresponding author

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Abstract

Updated data sets on terrestrial heat flow and thermal springs have been employed in outlining the nature of deep-seated geothermal resources of the Parana basin. A 1° x1° grid system was adopted for data processing and in determinations of vertical distributions of excess temperatures. The results obtained have led to an improved understanding of the occurrence of high temperature geothermal resources and allowed estimates of associated resource base. It has been possible to identify more than 20 crustal blocks where the resource base per unit area, referred to the accessible depth limit of 6 km, are in the range of $2x10^{11}$ to $9x10^{11}$ Joules. There are indications pointing to occurrence of medium temperature geothermal resources at depths of 4 to 6 km in several sectors of the central and western parts of the basin. The area extent of such blocks has dimensions of several tens of kilometers. Most high temperature resources occur within the well-known sectors of fault-controlled magmatic activity associated with the eruption of Serra Geral flood basalts. In addition, isolated pockets of high enthalpy geothermal resources are found to be present along the northwestern border. The results have also allowed better assessments of low temperature resources of the Guarani aquifer system, which span over large areas of southern Brazil, western Uruguay and northern Argentina.

1. Introduction

A notable advantage of geothermal energy resources is their ability to produce base-load power and heat, with a minimum of carbon emission to the environment. It has been demonstrated to be economically competitive, especially in cases where the resources are located at relatively shallow depths of no more than three kilometers. Recently, advances in drilling technology has emerged that can extract geothermal resources situated at depth ranges of three to six kilometers. It is customary to designate geothermal resources at such depths as Hot Wet Rock (HWR) and Hot Dry Rock (HDR), depending on the geothermal and hydrogeological characteristics of subsurface strata. The main obstacle in exploitation of geothermal energy from such deep-seated systems is the relatively high drilling cost associated with the early stages of exploration. Consequently, it is necessary to make best use of site-specific data on the subsurface thermal field and local geological characteristics, which provide as accurately as possible reliable assessments of subsurface energy sources.

Very few attempts seem to have been made in deriving resource assessments that also incorporate data on regional geologic and geophysical characteristics of subsurface strata Results of assessments of geothermal resources of Brazil have been reported in several earlier studies (Hamza et al, 1978; Hamza and Eston, 1983; Eston and Hamza, 1984; Hamza et al, 1990). More recently, assessments have also been carried on regional scales for several different parts in southern Brazil (Gomes and Hamza, 2004, 2005, 2006, 2007 and 2009; Hamza et al, 2005b). The results of such early works have led to identification of several targets for exploration of low enthalpy resources, situated generally at depths less than 3 km. In the present work, we report progress obtained in assessment of deep-seated geothermal resources in the Parana basin, in south Brazil.

2. Characteristics of the Parana Basin

This basin covers an area of nearly 1.5 million square kilometers in southern Brazil but extends also into the neighboring countries of Argentina and Uruguay. The map of Figure 1 illustrates its relative location with respect to the geologic features of south Brazil. The total thickness of the sediments varies from nearly three kilometers at the eastern border to almost seven kilometers in its central parts. The overall shape of this basin is approximately oval, with its major axis in the north – south direction.

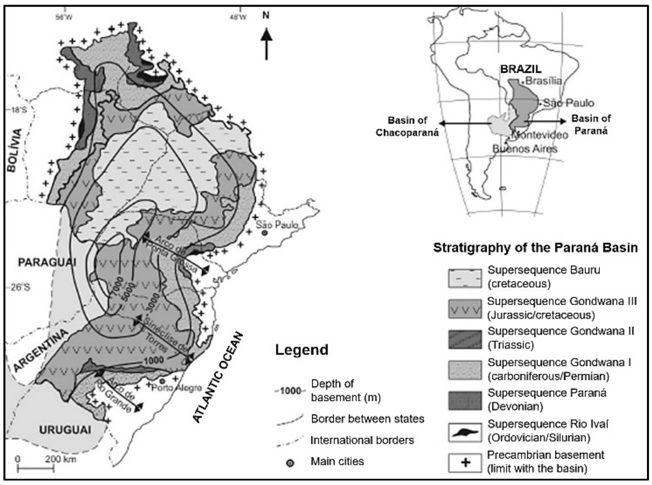

Figure 1 - Stratigraphic sequences of the Parana basin, Brazil (adapted from Milani and Ramos, 1998; Mori and Souza, 2010).

The evolution of Paraná Basin has been marked by several complex episodes of geologic activity (Soares et al, 1974; Almeida, 1980). Its lithologic record points to several stages, controlled by distinctly different tectonic and climatic factors. A multitude of depositional settings have been identified, with both marine and continental components, including glacial beds, desert sandstones and shallow marine to transitional facies (Zalán et al, 1987; Milani and Ramos, 1998). There are indications that the outlines of this basin were continuously reshaped by past tectonic activity. The last major tectono-thermal activity has been the eruption and deposition of flood basalts during the Cretaceous period. The depositional sequences of these units are illustrated in the schematic geologic cross-section of Figure 2. Note that a number of Paleozoic sedimentary sequences are buried beneath flood basalts of the Serra Geral formation. Milani et al (2007) recognized the main stratigraphic units as Rio Ivaí (Ordovician and Silurian age), Paraná (Devonian age), Gondwana I (Carboniferous – Eotriassic age), Gondwana II (Meso to Neotriassic age), Gondwana III (Neojurassic – Eocretaceous age) and Bauru (Neocretaceous age).

Seismic studies (Assumpção et al, 2013) reveal that crustal thickness of the region of Parana basin is relatively large, in the range of 38 to 45 km. Gravity and magnetic fields of this basin has been studied in some detail (Molina et al 1987; Mariani, 2012). Bouguer anomaly maps reveal values in the range of -70 to -35 mgal along north-south trending belts along the wester, eastern and central parts. Magnetic anomalies are positive in the northern and southwestern parts and negative in the eastern parts. Table 1 provides a simplified stratigraphic description of the sedimentary sequences in the Paraná basin.

Hydrogeological studies indicate that strata capable of hosting significant geothermal resources at depths greater than 3 km occur in the Taciba, Campo Mourao and Furnas formations of Devonian period. However, few studies have been carried out for determining porosity and permeabilities of these deep-seated formations. On the other hand, regional scale aquifers have been mapped at relatively shallow depths in the Botucatu and Piramboia formations of early Cretaceous period. It is often recognized as the Guarani aquifer system and covers an area of approximately 1.2 million square kilometers. Shading in yellow color indicate layers which are considered as having potential for extraction of geothermal resources.

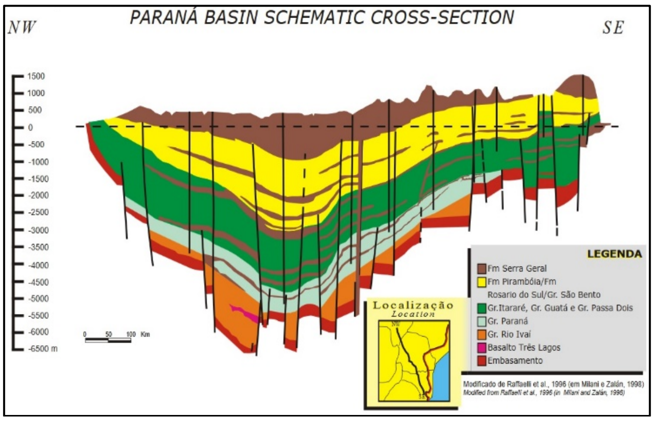

Figure 2 - Schematic geologic cross section across northwest southeast direction of Paraná basin (Adapted from Soares et al, 1974 and Milani and Zalán, 1998).

Table 1 - Simplified description of sedimentary sequences in the Paraná basin. Shading in yellow color indicate layers with potential for hosting low enthalpy geothermal resources.

Formation	Lithology	Z max (m)
Cachoeirinha	Sandstone	80
Bauru	Sandstone	260
Serra Geral	Tholeiitic basalts	1700
Botucatu	Sandstone cross-bedded	450
Pirambóia	Silt and Sandstone	200
Rio do Rasto	Sandstone	650
Teresina	Shales and Argillites	850
Serra Alta	Silts, shales, Argillites	100
Irati	Silts, Argillites, Shales	70
Palermo	Silts, Conglomerates	300
Rio Bonito	Silts and Shales	350
Taciba, C. Mourao, L. Azul	Medium Sandstone	150
Ponta Grossa	Shale, Sandstone, Silt	660
Furnas	Sandstone with cross bedding	337

3. Sources of Geothermal Data

The data employed in the present work are derived from the archives of the geothermal database, maintained by the National Observatory, Brazil. This database has recently been updated with temperature gradient and heat flow values for several new localities. The current geothermal database for the Parana basin includes results of measurements at 538 localities, of which 376 are situated in Brazil and the remaining 162 in neighboring countries (Argentina, Bolivia, Paraguay and Uruguay). The data distribution covers nine states in Southern Brazil (São Paulo, Paraná, Santa Catarina, Rio Grande do Sul, Mato Grosso, Mato Grosso do Sul, Goiás, Tocantins and Minas Gerais). Most of the Brazilian data were derived from the earlier works (Meister, 1973; Araújo, 1978; Vitorello et al, 1980; Eston et al, 1981; Hurter, 1987; Hurter and Pollack, 1996). The database employed in deriving geothermal maps, were discussed (Hamza and Muñoz, 1996; Hamza and Frangipani, 1990; Gomes and Hamza, 2004, 2005, 2006 and 2007; Hamza et al, 2005a, 2005b). Recently, new data acquired in the states of São Paulo, Santa Catarina and Goiás were also included. The map of Figure 3 indicates the locations of geothermal studies.

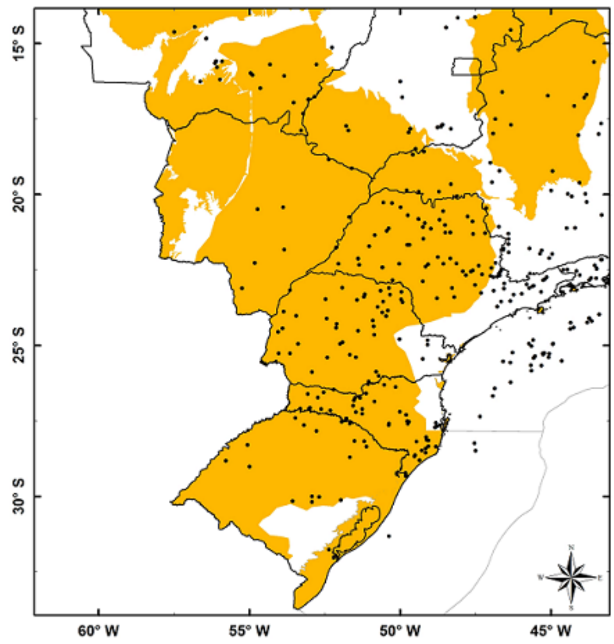

Figure 3 - Geothermal data distribution for Parana basin and neighboring areas.

Details of the techniques employed in geothermal data acquisition has been discussed in the earlier works of (Hamza and Muñoz, 1996; Gomes and Hamza, 2004, 2005). Several methods have been used in determining temperature gradients and heat flow, depending on the nature of techniques employed in acquisition of primary data. These may be classified as falling into groups designated as incremental logs (ITL, described as CVL kin earlier publications), bottom-hole temperature (BHT) and geochemical (GCL).

Examination of compiled information reveals large variations in the quality of primary data. Nevertheless, the database has been useful in determining mean values of temperature gradient and heat flow for 1^0 x 1^0 grid elements covering the entire area of this basin. Experimental heat flow data are currently available for slightly more than 70% of the grid elements. For purposes of the present work, estimated values derived from spherical harmonic expansion of the global heat flow field (Hamza et al, 2008) were assigned for those grid elements for which experimental data are not available. The gridded data has been useful in the past in deriving heat flow maps of four different regions in the basin (Gomes and Hamza, 2004, 2005; Hamza et al, 2005a).

4. Temperatures and Geothermal Gradients

The vertical distribution of temperatures determined using BHT data are illustrated in Figure 4. The continuous line in this figure is the least square fits to respective BHT data sets, while the dotted lines indicate approximate bounding (minimum and maximum) values, compatible with the observational data. The linear extrapolations of the least square fits to shallower levels have been terminated at depths corresponding to the values of mean annual surface temperatures; these latter ones are derived from local meteorological records. This procedure reveals the presence of vertical distributions of temperature, characterized by sharp changes at shallow depths. Such features in vertical distributions of temperatures have been interpreted by Pimentel and Hamza (2014) and Vieira et al (2014) as indicative of down flow of groundwater at shallow depths. Studies of the thermal structure at shallow depths are important in understanding the nature of deep flow systems.

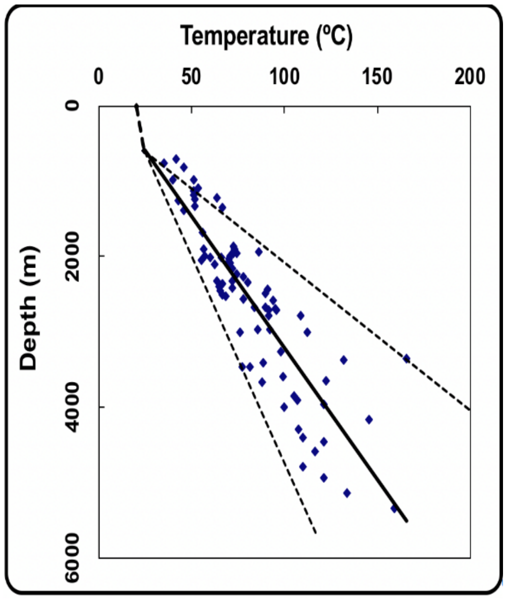

Figure 4 - Vertical distribution of bottom-hole temperatures in the Parana basin.

The mean values of gradients obtained using these methods are $24,1^0$C/km for ITL, 23.9^0C/km for BHT and 30.8^0C/km for GCL. The mean gradient for all data is 23^0C/km and the mean extrapolated surface temperature is 22.5^0C. The distribution of geothermal gradients, illustrated in Figure 5, reveal that relatively high values occur in the northern and southeastern parts. Northeastern and southwestern parts of the basins have relatively low geothermal gradients. Intermediate values occur in the remaining regions. Pimentel and Hamza (2014) and Vieira et al (2014) have argued that low geothermal gradients are associated with regions of significant down flows of groundwater in deeper strata.

5. Thermal Conductivity

The thermal conductivity data compiled in this work is based on results of measurements reported in earlier studies, which has been discussed in detail (Hamza et al, 2005a; Gomes and Hamza, 2006; Hurter and Pollack, 1996). The techniques used for thermal conductivity measurements include divided-bar (Hamza et al, 1980), line source (Marangoni and Hamza, 1983) and plane source methods (Gomes and Hamza, 2006).

Values of thermal conductivity lower than 2W/m/K were found for basalt rich Serra Geral formation and shale rich Estrada Nova, Serra Alta and Tatui formations. Values higher than 4W/m/K are found for sandstone rich formations of Aquidauana, Furnas and Vila Maria. A selected set of values for the main formations, as per the stratigraphic sequence is presented in table (Hamza and Eston, 1983).

6. Heat Flow

Heat flow values were calculated as the product of geothermal gradient and thermal conductivity for 545 sites in the Parana basin and adjacent areas. The mean values of heat flow obtained by the different methods are in the range of 62 to 72mW/m^2. Gomes (2009) has provided a detailed summary.

The spatial distribution of heat flow is illustrated in the map of Figure 6. It is clear from this map that the basin is characterized by a region of relatively low heat flow along a northeast – southwest trending belt. Heat flow is relatively high along the western and eastern borders.

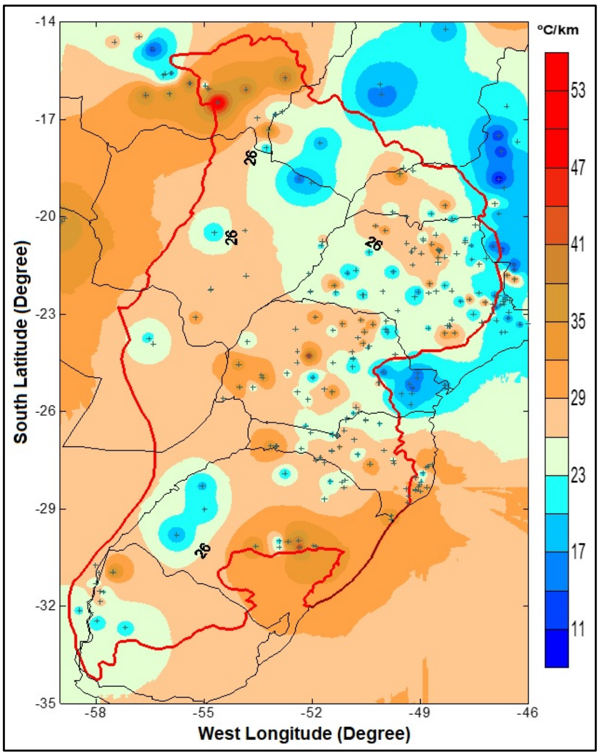

Figure 5 - Updated geothermal gradient map of the Parana basin. The curve in red color is the outline of the basin. Black lines indicate boundaries of states.

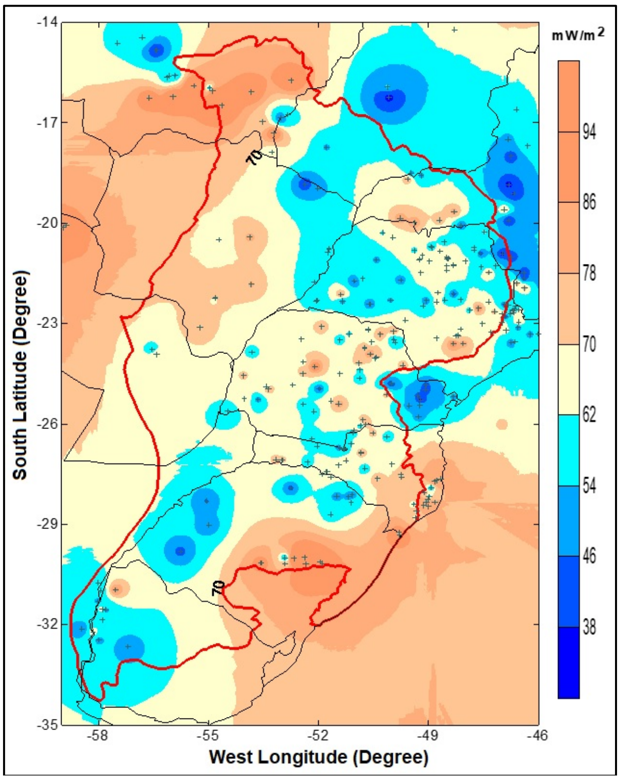

Figure 6 - Updated heat flow map of the Parana basin.

Table 2 - Thermal conductivity values of selected rock formations.

Formation	Rock Type	N	λ (W/m/K)
Bauru	Sand	64	3.7
Serra Geral	Basalt	520	1.8
Botucatu	Eolian Sandstone	279	3.8
Piramboia	Silty Sand	10	2.7
Rio do Rasto	Silt and Sand	87	2.3
Terezina	Shaly sand	39	2.2
Estrada Nova	Shale	27	1.9
Serra Alta	Shale and Sand	35	2.0
Irati	Shale	53	2.3
Palermo	Silt and sand	70	2.7
Tatui	Silty sand	9	1.8
Rio Bonito	Sandstone	54	2.8
Itarare	Sandy silt	171	3.1
Ponta Grossa	Shale	32	2.7
Furnas	Sandstone	32	4.0

7. Intra Basin Temperatures

Temperatures at depths of main basin formations were calculated based on results of geothermal gradients, thermal conductivity and heat flow. One of the remarkable feature turned out to be considerable variations in the vertical distribution of temperatures. This can be seen in the depths of isotherms of 30 and 60 C, along the east – west and north – south profiles, illustrated in Figure 7.

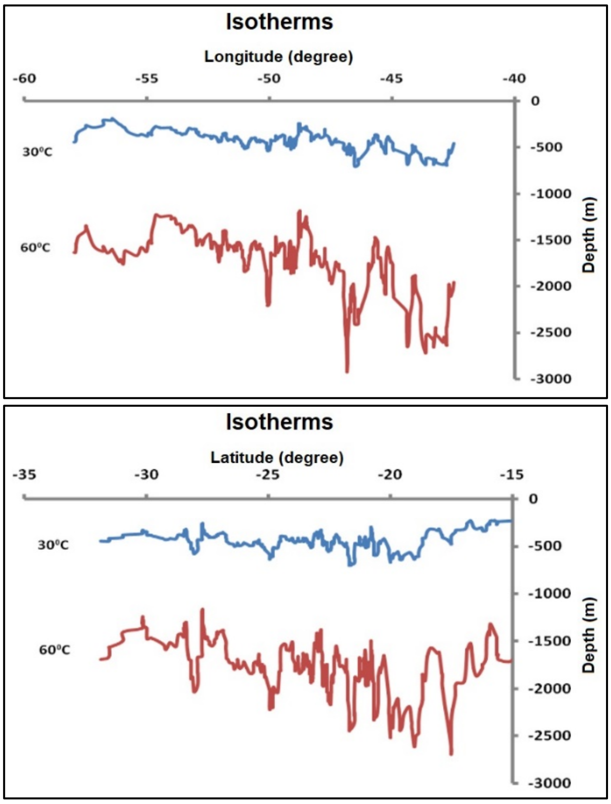

Figure 7 - Depths of isotherms of 30 and 60°C along east west (top panel) and north-south (bottom panel) profiles across the Parana basin.

In the present context, the interest has been in understanding the lateral variations in temperatures across the basin. The depth levels chosen for this purpose are 1km, 3km and 5km. The spatial distributions of temperatures, calculated for these depths are presented in the three panels of Figures 8a and 8b. Referring to the top panel of this figure we note that temperatures are higher than 44^{0}C at depths of less than one km in the northern parts of the basin. The lower panel of this figure indicate lateral distribution of temperatures at depths of 3km. In this case, most parts of the basin it is higher than 80^{0}C.

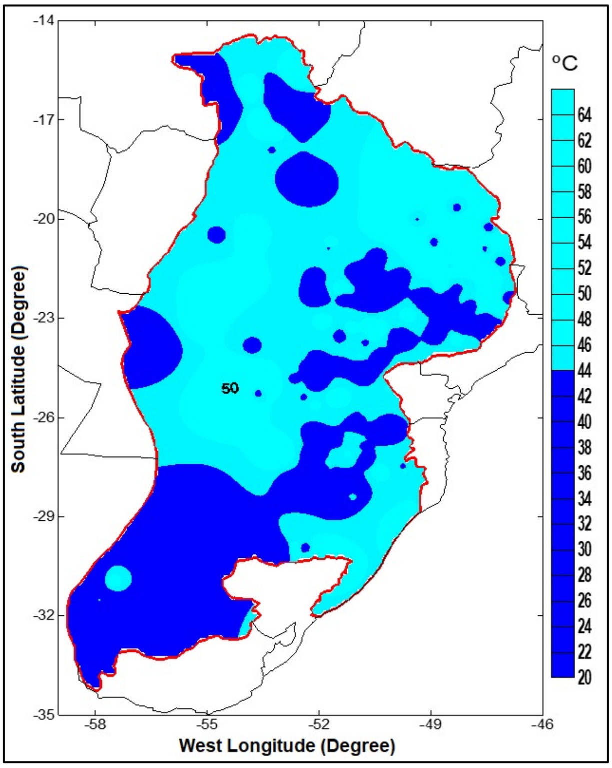

Figure 8a - Temperature distributions at 1km depth in the Parana basin.

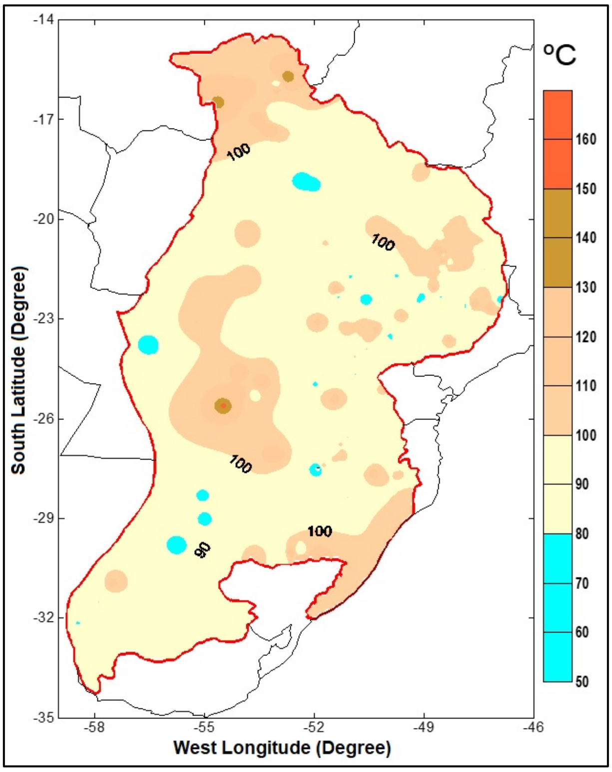

Figure 8b - Temperature distributions at 3km depth in the Parana basin.

Figure 9 illustrates the lateral distribution of temperatures at the depth level of 5km. The results point to several areas where temperatures are higher than 150^{0}C.

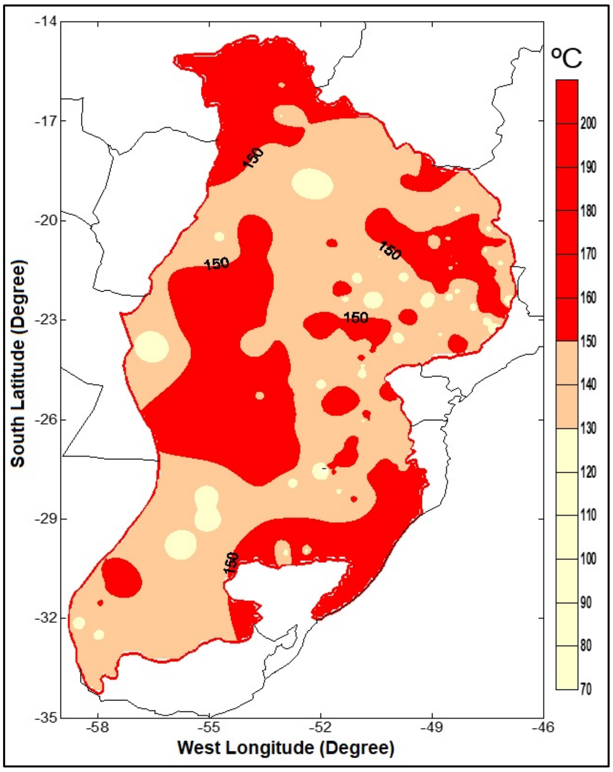

Figure 9 - Temperature distribution at 5km depth in the Parana basin.

8. Estimates of Resource base

The resource base calculations were carried out following the methodology discussed in earlier studies (Muffler and Cataldi, 1978). Volumetric method was considered adequate for the present purpose. In this method the resource base per unit area is calculated as the excess thermal energy in the layer up to a depth of 6km, the reference temperature value for energy calculations being the surface temperature. The excess temperature (ΔT)was calculated using the relation:

$$T_e = \frac{q_0}{\lambda} z - \frac{A_0}{2\lambda} z^2 \quad (1)$$

where q_0 the surface heat flux, z the thickness of the layer, λ the thermal conductivity and A_0 the radiogenic heat productivity at the surface.

The basin area was divided into equal longitude cells. The resource base (Q_{RBi}) for the i_{th} cell, of thickness di, associated with the temperature distribution given by equation (1), is calculated using the relation:

$$Q_{RB\,i} = \rho_i c_{pi} A_i d_i (T_i - T_{0i}) \quad (2)$$

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

Analysis of resources based on the lateral distribution of temperatures point to widespread occurrence of low temperature resources at depths of up to one kilometer. Resources associated with the Guarani aquifer at depths less than 2km are examples. Medium enthalpy resources occur at depths of 3 to 5km. Such resources may be found in confined aquifers of Furnas and Ponta Grossa. High enthalpy resources, with temperatures higher than 150^0C, are expected in the northwestern and central parts of the basin. The map of Figure 10 illustrates the distribution of total resource base. Resource base values higher than $5x10^{11}$J mostly in the central and northwestern segments of the basin.

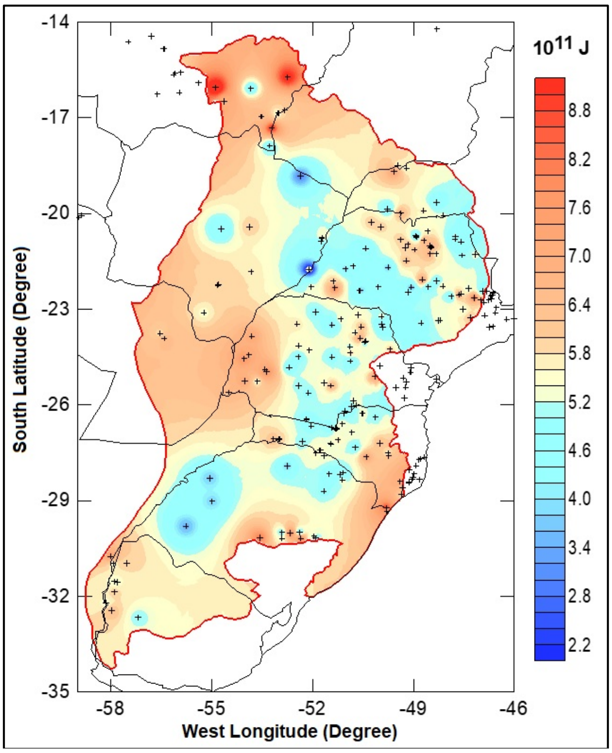

Figure 10 - Map of geothermal resource base, referred to the accessible depth of 6km for the Parana basin.

9. Discussion and Conclusions

Unlike previous studies the results obtained in the present work have led to assessments of resources that incorporate not only borehole temperature and heat flow data but also available information on structure and physical properties of the crustal layers. There are indications that this procedure has led to improvements in our understanding of the spatial distribution of both low and high enthalpy geothermal resources in the Parana basin. In particular, it is now possible to understand better the relations between origin of surface manifestations of geothermal fluids and the resource base in geothermal areas. Another important point emerging from the results of the present work is that medium and high enthalpy resources occur mostly in the western parts while low enthalpy resources occur in the eastern parts.

10. Acknowledgments

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