Updated Assessment of Geothermal Resources in Brazil

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Abstract

Assessments of geothermal resources of Brazil are presented that include results of recent surveys carried out in the states of Tocantins, Pará and Mato Grosso. Currently, it is based on data acquired at over 1,100 sites as well as information on hydrothermal and energy use on thermal fluid discharge systems at over 110 localities. The total resource base, referred to the accessible depth limit of 3km, is estimated at 1,800 TJ. This is nearly 25% less than previous calculations, as it allows for estimated cooling effects of regional scale groundwater circulation in deep sedimentary strata. A significant low temperature geothermal anomaly has been discovered in the eastern part of the state of Tocantins. Nevertheless, potential for high temperature geothermal systems appears to be restricted to the Atlantic islands of Fernando de Noronha and Trindade. The available parts of resources have been calculated based on regionally averaged values of porosity and permeability. It is estimated to be of the order of 4 TJ, but only a small fraction is being currently exploited. The total capacity of low temperature geothermal systems under economic exploitation is estimated at 365 MWt, while the annual energy use is estimated to be of the order of 6,540 TJ. About a dozen of the spring systems account for the bulk of this capacity. Most of them are located in west central Brazil (in the states of Goiás and Mato Grosso) and in the south (in the state of Santa Catarina). The potential for large scale exploitation of low temperature geothermal water for industrial use and space heating is considered to be significant in the central parts of the Paraná basin (situated at southern and southeastern Brazil), where cold winter seasons prevail under subtropical climate conditions.

Introduction

According to recent compilations of information on energy use geothermal contribution is estimated to be over 360MWt. Geothermal springs are major public attractions in Brazil and have contributed to significant local and regional tourist developments in specific areas. Nevertheless, lack of systematic studies has contributed to poor understanding of the physical and chemical characteristics of geothermal resources and their regional distribution. It is in this context the present study was undertaken. Early works on the evaluation of the potential for geothermal energy and assessment of resources in Brazil were carried out by Hamza et al. (1978) and Hamza and Eston (1983). These early works made extensive use of the results of heat flow measurements. At the beginning of the last decade, attempts were made for assessment of the resources associated with thermal springs in the states of Mato Grosso, Goiás and Tocantins. Hamza et al. (2005) discussed the results of this work, carried out in collaboration with the International Institute of Geothermal Research (IIRG) of Italy. Hamza and Carneiro (2004) have examined the spatial distributions of these earlier estimates of the resource base. Systems with temperatures lower than 90°C constitute the most common type of geothermal reservoirs in Brazil (Hurter et al, 1983).

A major weakness of these earlier studies is that the resource estimates are based mainly on local values of geothermal gradients and heat flow. With the exception of the study by Hamza et al. (2010), few attempts have been made in incorporating information on regional geologic and geophysical characteristics of subsurface strata in resource assessments. In the present work, a new approach has been adopted that takes into consideration not only available data sets on near surface temperatures and heat flow but also supplementary information on regional lithology and hydrologic characteristics of subsurface strata, that have direct bearings on the occurrence of geothermal resources

Sources of Data

The Geothermal Laboratory of the National Observatory compiled basic data on the physical and chemical characteristics of thermal systems. These digests also include data on the thermal and physical properties of major geological formations in the upper crust, the temperature distribution in vertical boreholes and wells, as well as terrestrial heat flow estimates (Vieira and Hamza, 2011). These data sets have been useful in determining estimates of geothermal resources at various levels of depth in the upper crust. Despite progress in the acquisition of new data exist significant contrasts in their distribution. There is the existence of several regions of low data density, especially in the north central part of the country. Currently the data set used in this study includes a total of 1270 experimental data.

The density of the data is relatively higher in the south and southeast, where there is a significant concentration of these data compared to the Northeast. The spatial distribution is not homogeneous and the acquisition of geothermal data on a large scale is a costly and time consuming task. Given this problem, it was necessary to use estimates of a secondary nature to obtain a better representation, both qualitatively and quantitatively, the geothermal field of the study area. The geothermal database compiled for the purpose of this paper includes information about the surface temperature, temperature logs of wells and boreholes, experimental measurements and indirect estimates through empirical relationship between age and tectonic heat flow proposed by Polyak and Smirnov (1968) and Hamza and Verma (1969).

The geographic distribution of this set of integrated data (observational data and theoretical values) is illustrated in the figure map (1), where it was used a 20 x 20 mesh system for the representation of data sets. In this figure, the red-colored dots indicate cells with the experimental data points and the color blue cells with the theoretical heat flux values.

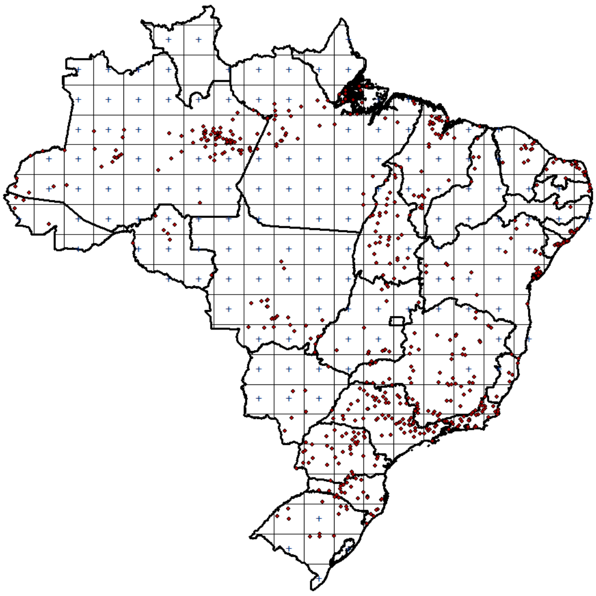

Figure (1) Locations of geothermal studies in Brazil

Crustal temperatures

The compilations of the geothermal database have been useful in determining vertical distributions of temperatures in the upper crust. A simple one-dimensional heat conduction model, that incorporates the effects of vertical variations in thermal conductivity and radiogenic heat production, was used for this purpose. The relation for "excess temperature" (ΔT) over the mean surface temperature is given by the relation:

$$\Delta T = \frac{q_0}{k} d - \frac{A_{0rad}\, d^2}{2k}\left(1 - e^{-z/D}\right)$$

where q_0 is the surface heat flux, A_0 is radiogenic heat productivity and k is the thermal conductivity. The values of A_0 is derived from empirical relations (Cermak et al, 1990) relating to crustal seismic velocities with radiogenic heat productivity. The thermal conductivity values of the sedimentary layers were derived from the heat flow database. Regional distribution of excess temperatures, referred to a depth of 3 km, is illustrated in the map of Figure 2.

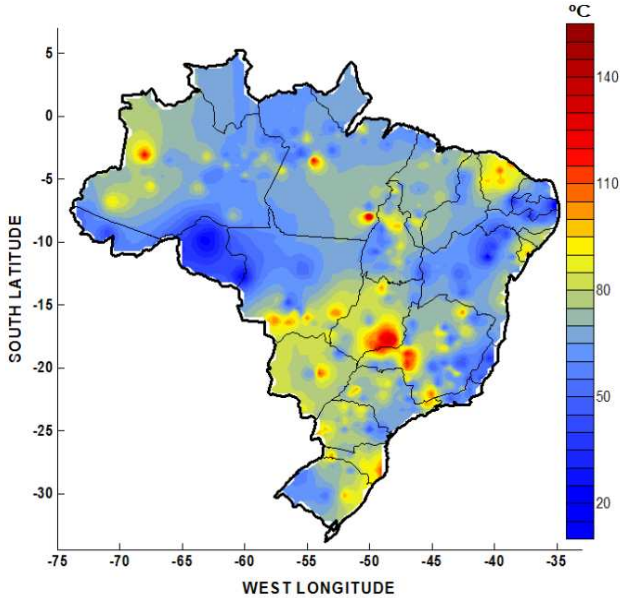

Figure (2): Map of excess temperatures referred to depth of 3 km

Calculations of resource base

The resource base calculations were carried out following the methodology proposed in earlier studies (e.g. Muffler and Cataldi, 1978). Volumetric method was considered adequate for the present purpose. In this method, the resource base is calculated as the excess thermal energy in the layer, the reference value being the surface temperature. The resource base (Q_{RB}) of thickness d, associated with the temperature distribution given by equation (1), is derived using the relation:

$$Q_{RB\ i} = \rho_i\, c_{pi}\, A_i\, d_i\,(T_i - T_0)$$

where ρ_i is the average density of the i^{th} layer, c_{pi} the specific heat, A_i the area of the cell, T_i the bottom temperature and T_0 upper surface temperature. In the present work, a reference depth of 3 km was chosen in calculations of the resource base. The regional distribution of the resource base, referred to this depth limit is illustrated in the map of Figure 3.

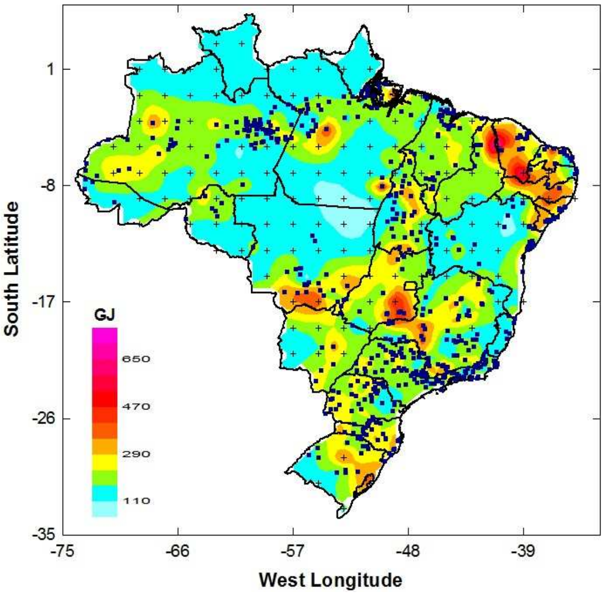

Figure (3) Map of resource base (in GJ) referred to depth of 3 km

Estimates of recoverable resources

The recoverable resource is usually defined as that part of the resource base associated with pore fluids that can be extracted using current technology. In areas of positive geothermal gradients, temperatures of the rock matrix and the pore fluids increase with depth. However, porosity and permeability of most common rocks decrease with depth, which imply corresponding decrease in quantity of circulating fluids in deeper levels. We examine first the nature of opposing roles of temperature and porosity variations with depth.
The relation for the total geothermal resource (Q) of a volume element (of area A and thickness h) with rock temperature T_r and porosity ϕ may be written as:

$$Q = \left[\phi C_f + (1-\phi) C_r\right]\left[T_r - T_0\right] A h$$

where C_f and C_r are the heat capacities of the fluid and rock matrix respectively. The variation of T_r with depth Z depends on the local value of geothermal gradient (g). The variation of porosity ϕ with depth Z may be represented by a relation of the type:

$$\phi = \phi_0 e^{-Z/D}$$

where D is the logarithmic decrement of porosity with depth.

Applying the above procedure to the results of the present work revealed that the maximum in recoverable resources occurs in the depth range of 2,500 to 3,500 meters. A summary of the estimates of excess temperatures (T_e), resource base per unit area (RBUA) and recoverable resources per unit area (RRUA) is given in Table 1. As expected, regions with large numbers of thermal springs (such as the States of Santa Catarina, Goiás, Minas Gerais and Mato Grosso) are characterized by relatively high values of recoverable resources. The resource base is high in the state of Ceará because of the relatively high values of excess temperatures. However, the recoverable resource is estimated to be relatively low because of reduced porosity of metamorphic rocks. Recoverable resources are estimated to be less than 10 GJ in ten States.

Table 1. Estimates of excess temperature (Te), resource base per unit area (RBUA) and recoverable resource per unit area (RRUA), in 26 States of Brazil. N_R is number of grid elements used in resource estimates.

State / Region	N_R	Te (°C)	RBUA (10^9 J)	RRUA (10^9J)
Santa Catarina	23	86.2	263.0	20.6
Goiás	14	96.1	286.3	18.9
Minas Gerais	60	71.7	231.6	18.1
Mato Grosso	24	70.3	235.1	17.4
Tocantins	31	70.2	225.9	14.4
Ceará	10	97.9	285.7	14.3
Mato Grosso do Sul	7	75.6	256.1	12.8
Bahia	25	50.9	183.1	12.7
Sergipe	11	86.2	255.0	12.8
Alagoas	9	78.9	233.5	11.7
Paraná	39	76.2	227.3	11.4
São Paulo	69	74.0	217.9	10.9
Rio Grande do Sul	15	75.4	211.4	10.6
Amazonas	72	69.1	205.4	10.6
Maranhão	25	70.1	203.1	10.2
Rio Grande do Norte	14	66.8	202.3	10.1
Pará	40	65.0	192.1	9.6
Rio de Janeiro	27	62.0	179.9	9.0
Piauí	4	56.1	165.2	8.3
Acre	4	49.3	114.8	7.2
Amapá	2	61.3	102.1	5.1
Pernambuco	1	42.5	42.5	2.1
Paraiba	5	25.4	26.7	1.3
Rondônia	7	26.6	26.6	1.3
Roraima	1	26.1	26.1	1.3
Espirito Santo	6	43.3	15.5	0.8
Average			**201**	**11.8**

The analysis of the available geothermal data indicates that recoverable resources are significant mainly in areas with sediment cover and in areas of high fracture density. The deeper parts of the upper crust have very little porosity and are incapable of holding significant amount of recoverable resources. In view of these considerations, the resource base calculations have been limited to a maximum depth limit of 3 km. The map of Figure (4) illustrates spatial distribution of the recoverable part of the resource base, referred to the depth limit of 3 km within the continental segment of the Brazilian territory.

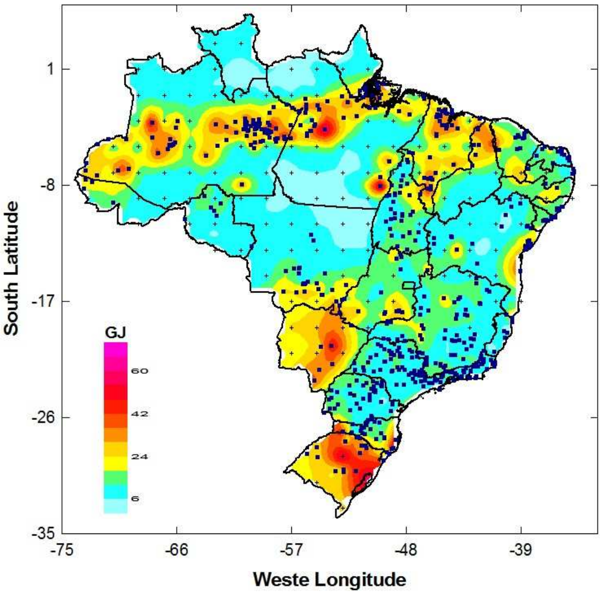

Figure (4). Map of recoverable resource (in GJ) referred to depth of 3 km.

Use of low temperature geothermal resources

Geothermal Laboratory of the National Observatory has compiled information on the main geothermal systems currently being exploited commercially in Brazil. This compilation includes data on flow rates, range of use of temperatures and chemical characteristics of thermal fluids. Following the practice adopted in earlier works, we found it convenient to classify the information on spring systems into groups, based on such key factors as perspectives for direct use, proximity of large urban centers and local climate characteristics. They are designated as BRT (Bathing, Recreation and Tourism), PIS (Potential for Industrial use and Space heating) and TDB (Therapeutic, Drinking and Bathing) groups. The geographic distribution of the main thermal and mineral springs belonging to the three above-mentioned groups is illustrated in Figure (5). As can be seen in this figure, the concentration of thermal springs is relatively high in southern and south-central parts of Brazil, compared with the northern parts. Also indicated in this figure are the sites where industrial use of thermal water has been made.

The spring systems belonging to the BRT group have an estimated total thermal capacity of 16 MWt and an annual energy use of about 189 TJ. The localities of these thermal springs have become popular tourist attractions over the last few decades. Currently such small-scale thermal and mineral spas are visited by an estimated 1.5 million tourists per year. This in turn has spurred considerable local economic activity. The emphasis at these thermal spas and tourist centers is on entertainment and physical conditioning under programs for revitalizing the body in a relaxing environment. Larger spring systems belonging to the PIS group have an estimated total thermal capacity of 343 MWt and an annual energy use of about 6,291 TJ. Currently the thermal resources at these sites are being used almost exclusively for bathing and recreation, in spite of their considerable potential for industrial applications and space heating. Industrial use of thermal water has so far been attempted only in a few localities. In the town of Taubaté, in southeastern São Paulo geothermal water at 48^{o}C was used, during the 1970s and 1980s, for industrial wood processing (pre-heating prior to peeling). In Cornélio Procópio, in the state of Paraná, geothermal water at 50oC pumped from a 950-meter deep well has been used, since 1980, as pre-heated water for boilers, in industrial production of coffee powder. The spring systems belonging to the TDB group have an estimated total thermal capacity of three MWt and an annual energy use of about 56 TJ. Exploration of non-thermal mineral water for therapeutic purposes is quite widespread. According to recent estimates, revenues generated by the mineral water industry make up a significant component of the economy in many municipalities. In this respect, it is convenient to note that the list given in Table 2 and the sites indicated in Figure 6 represent only a tiny fraction of the current total mineral water production

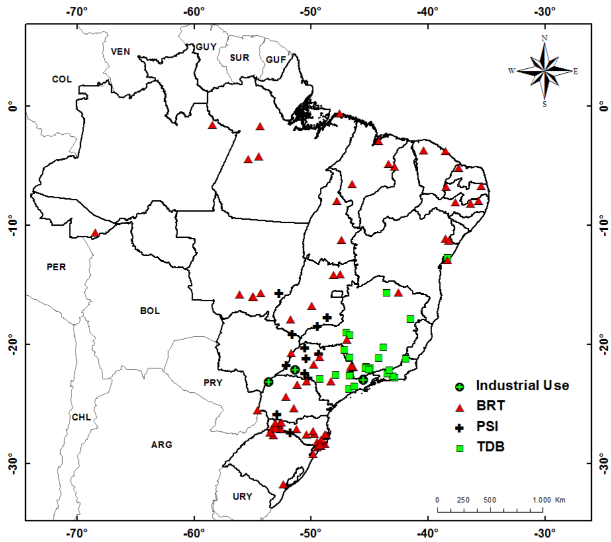

Figure (5) Locations of major thermal spring systems in Brazil. See text for explanations of abbreviations used (BRT, PIS and TDB).

Future perspectives

In evaluations of suitable sites for exploitation of resources, use has been made of information on thickness, density and seismic velocity of the crustal layers in addition to the temperature and heat flow data sets. The relevant information available in the global crustal data compilations by Mooney et al., (1998) and by Bassin et al. (2000) are considered sufficient for the present purpose. In these data sets, the crust is assumed to be composed of five sequential layers, classified as soft sediments, hard sediments, upper crust, middle crust and lower crust. In the present work, we have introduced a modification that allows for the eventual existence of layers with high fracture density at depths less than 5 km. Such layers are capable of holding significant amount of recoverable resources. Large thicknesses of sedimentary strata are present in the central parts of basins in the Amazon region, Parnaiba and Paraná. Such basins are considered as suitable targets for exploitation of geothermal resources.

Other targets considered suitable for exploitation of resources are some of the Precambrian areas in the states of Goiás and Tocantins where layers of high fracture density exist in the upper crust. In addition, there are indications of medium enthalpy resources in the basal parts of the Parana basin (Gomes, 2017), at depths greater than 5km. Results of aeromagnetic surveys used in mapping depths of Curie isotherms (Guimaraes et al, 2014) have allowed identification of several magma intrusions in deep crustal layers, mainly in the state of Minas Gerais. Recent results of magneto-telluric studies (Santos et al, 2013) have identified the existence of a major anomaly in the central parts of Pernambuco state, in northeast Brazil. There are indications that this anomaly is of geothermal origin. Locations of such suspected medium to high enthalpy resources are indicated in the map of Figure 6:

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 South American continent. In particular, it is now possible to understand better the relations between and the crustal layer of origin of surface manifestations of geothermal fluids and the resource base in geothermal areas.

We have provided separate resource estimates for the main layers in the upper parts of the crust. It is possible to combine these individual contributions to the resource base in obtaining estimates of total resource base. Note that the maximum value of the integrated resource base is 100 TJ. This value is significantly different from that obtained in previous studies. Another important point emerging from the results of the present work is that medium to high enthalpy resources may be present at depths greater than 5km in the southern and northwestern parts of Brazil.

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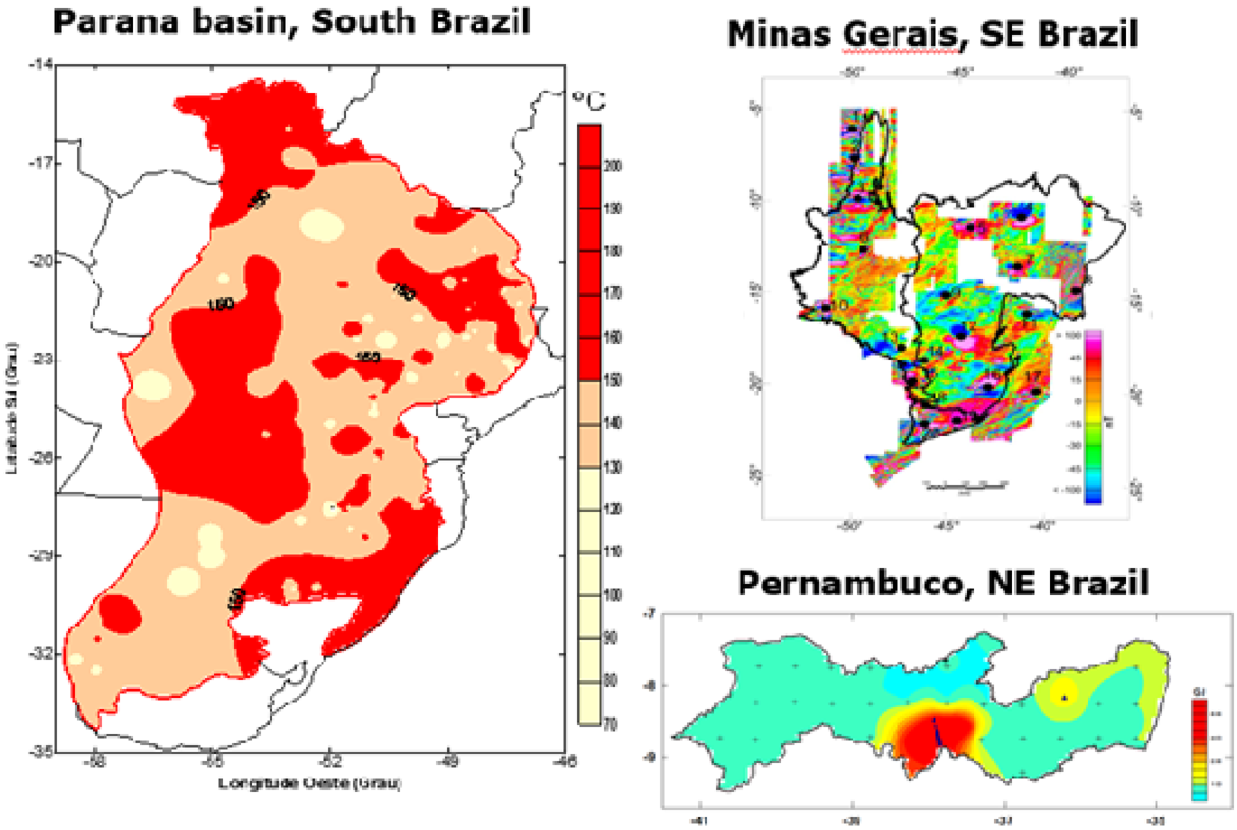

Figure (6) Possible localities of medium to high enthalpy geothermal resources within the Brazilian territory. The upper right panel indicates locations of deep crustal magma intrusions identified in aeromagnetic surveys. The lower panel indicates the anomaly at 5km depth, identified in magneto telluric studies. See text for details.