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Geothermal Resource Base for South America: A Continental Perspective

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ABSTRACT

Recently updated data sets on crustal seismic velocities, gravity anomalies, radiogenic heat production, terrestrial heat flow and thermal springs have been employed in outlining regional variations in the thermal characteristics of the South American continental lithosphere. A 2^ox2^o grid system was adopted for data processing and in determinations of vertical distributions of excess temperatures. The results obtained have lead to an improved understanding of the tectonic control on the occurrence of geothermal resources and allowed estimates of 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 3 km, are in the range of 10^{13} to 10^{14} Joules. The area extent of the blocks ranges from several tens to hundreds of kilometers. Most of high temperature resources occur within the well known sectors of magmatic activity in southern and central Chile, Altiplano region in Bolivia, and several localities along the magmatic arc covering western Ecuador, central volcanic belt of Colombia and southern Venezuela. In addition, isolated pockets of geothermal resources are found to be present along the western Andean belt in Peru. There are indications pointing to occurrence of medium temperature geothermal resources at depths of 3 to 5 km in some sectors of the eastern parts of the continent, mainly in the northeastern and central parts of Brazil. 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

Assessments of geothermal resources have been made for several countries in South America. These include Argentina (Miranda and Pesce, 1997; Pesce, 1995; Pesce, 2000; Pesce, 2005), Bolivia (Delgadillo, 1997), Brazil (Hamza et al, 1978; Hamza and Eston, 1983; Hamza et al, 2005), Chile (Lahsen, 1988; Lahsen et al, 2005), Colombia (Alfaro et al, 2000), Ecuador (Ameida, 1988; Beate and Salgado, 2005), Peru (Diaz and Guillermo, 1988; Parodi, 1975,) and Venezuela (Almandoz and Rojas, 1988; Urbani, 1989). Many of these assessments rely almost exclusively on results of local geothermal measurements. In addition, evaluations of geothermal energy potential have been carried out for areas characterized by occurrences of natural thermal fluid discharges at the surface, mainly in the Andean region. According to Battocletti (1999; Huttrer, 2001) the total power potential for such geothermal areas is estimated to be 14660 MWe. Table (1) provides a summary of geothermal power potential, derived from these earlier studies, for the continental area of South America. As expected almost all of the high enthalpy resources are located in the Andean region. Only low enthalpy resources have so far been identified in the eastern part of the continent.

Table (1) Estimates of geothermal power potential for selected localities. N_{HE} and N_{LE} refer to numbers of localities with high and low enthalpy resources (* - Battocletti, 1999 (MWe); ** - present work (MWt)).

Group	Country	N_{HE}	N_{LE}	Potential (MW)
High Enthalpy	Argentina	4	17	2010*
	Bolivia	4	6	2490*
	Chile	12		2350*
	Colombia	5		2210*
	Ecuador	5		1700*
	Peru	12		2990*
	Venezuela	3		910*
Low Enthalpy	Brazil	1?	25	250**
	Uruguay	0	5	50**
	Paraguay	0	5	10**
Unknown	British Guiana			
	French Guiana			
	Suriname			

A major weakness of these earlier studies is that the resource estimates are based primarily on temperature data from geothermal areas. Very few attempts seem to have been made so far in deriving resource assessments that also incorporate data on regional geologic and geophysical characteristics of subsurface strata. In the present work, a new approach has been adopted that take into consideration not only available information on near surface temperature and heat flow but also supplementary data on regional lithologic and hydrologic characteristics of subsurface strata, that have direct bearings on the occurrence of geothermal resources.

2. SOURCES OF DATA

The temperature and heat flow data employed in the present work are derived from the geothermal database for South America, maintained by the National Observatory, Brazil. Major difficulties in organizing this database arise from the large variations in the quality of information and the limited availability of reliable experimental data. Nevertheless, information that compose this data base has been useful in determining mean values of temperature gradient and heat flow for 2^0 x 2^0 grid systems covering significant parts of the continental area. Experimental heat flow data are currently available for slightly more than 50% of the grid elements. The gridded data has been useful in the past in deriving heat flow maps of the South American continent (Hamza and Muñoz, 1996; Hamza et al, 2005). For purposes of the present work estimated values derived from spherical harmonic expansion of the global heat flow field (Cardoso, 2006; Hamza et al, 2008) were used for those grid elements for which experimental data are not available. The map of Figure (1) illustrates the distribution of experimental and estimated values.

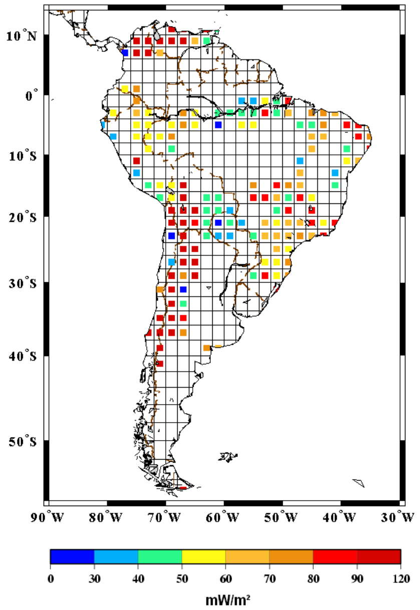

Figure 1: Discretized representation (2°x2° grids) of geothermal data distribution for South America. The colored grids indicate areas with experimental data. Heat flow values for the remaining cells were calculated using spherical harmonic coefficients derived from global heat flow map (Cardoso, 2006; Hamza et al, 2008).

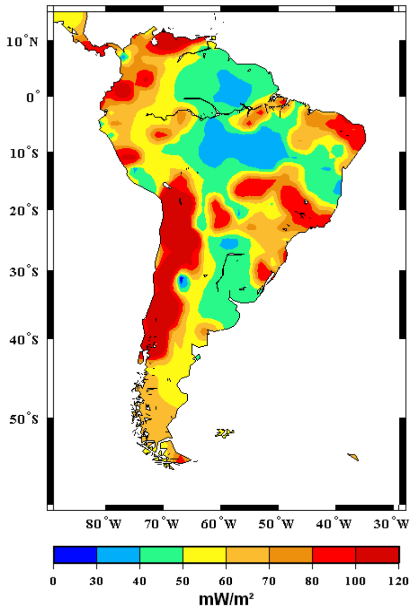

Figure 2: New heat flow map of South America based on updated data base and estimated values based on spherical harmonic expansion to degree 36 of the global heat flow (Hamza et al, 2008).

This data base has recently been updated with temperature gradient and heat flow values for several new localities. Most of the new data are from the sedimentary basins of Catatumba, Cusiana, Cupiaga, Eastern Cordillera, Llanos, Magdalena and Putumayo, situated in the Andean region of Colombia (Alfaro, Personal communication), coastal areas of eastern Brazil (in the states of Ceará, Rio Grande do Norte, Bahia and Espirito Santo) and the São Francisco craton in central Brazil. The new heat flow map of South America derived from the updated data base is presented in Figure (2).

3. CRUSTAL MODEL USED IN RESOURCE ASSESSMENT

In addition to the temperature and heat flow data sets use has also been made, in the present work, of complementary information on thickness, density and seismic velocity of the crustal layers. For this purpose use has been made of global crustal data compilations by Mooney et al, (1998) and by Bassin et al (2000). The compilation of Bassin et al (2000) provides mean values for 2^0 x 2^0 grid elements. 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. A schematic representation of the crustal model adopted for resource estimates is illustrated in Figure (3).

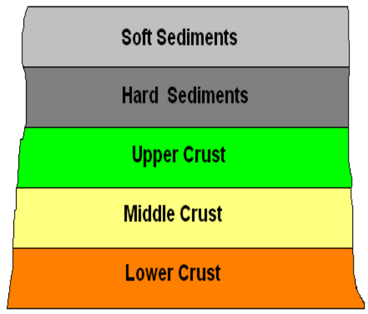

Figure 3: Schematic representation of the crustal model adopted for resource estimates.

It often happens that all three top layers (soft sediments, hard sediments and upper crust) may not be present at depths less than 10km in all crustal segments. In fact three possible types of crustal types can be envisaged:

Type 1- composed of just the sedimentary layers (soft and/or hard), but without upper crust;

Type 2- devoid of any sedimentary cover, hence only upper crust may be present;

Type 3- where both sediment layers and upper crust are present.

In this last case, three subcategories may exist:

Type 3a: soft sediment and upper crust;

Type 3b: hard sediment and upper crust

Type 3c: soft and hard sediments as well as upper crust.

Following Muffler and Cataldi (1978) we have limited the resource base calculations to the maximum depth limit of 10 km. Since the minimum thickness of the layer classified as upper crust is 10 km it is not necessary to take into consideration resources associated with the middle and lower crustal layers. In some resource assessment studies depth limit for accessible resource base is set as 3 km. In the present work this limit has been adopted in calculating the total resource base.

The maps of Figures (4a), (4b) and (4c) illustrate spatial distributions of the thicknesses of these layers in South America. Note that the thickness of soft sediments (see Figure 4a) is in excess of 1.5km in the northern parts of Colombia and Venezuela. It is in the range of 0.5 to 1.5km in most parts of the Pre Cordilleran and Paleozoic basins. Soft sediments are present as a thin layer with thickness less than 500m in large parts of the Precambrian cratonic areas and in the Andean ranges.

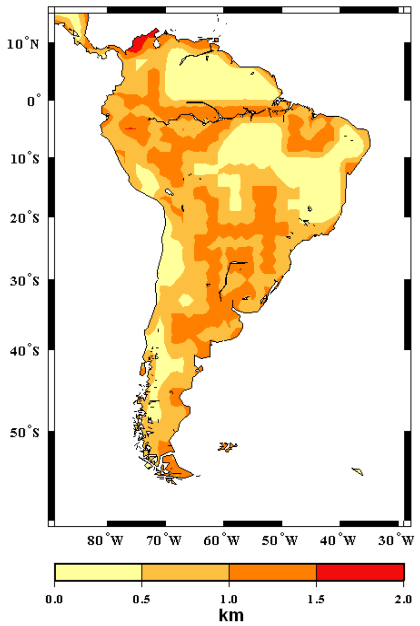

Figure 4a: Map of thickness of soft sedimentary layers, derived from crustal data of Bassin et al (2000)..

The hard sedimentary layers have thicknesses reaching up to 8km. Regions with thickness greater than 2km seem to be situated along an arc shaped belt extending from Venezuela to south Brazil. It is practically absent in Precambrian cratonic areas (see Figure 4b).

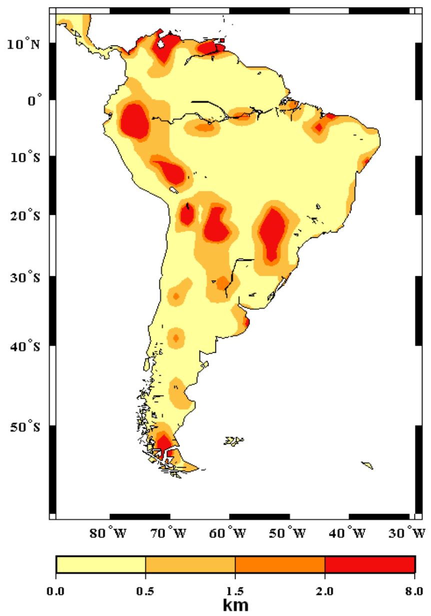

Figure 4b: Map of thickness of hard sediment layers, derived from crustal data of Bassin et al (2000).

On the other hand, thickness variations of upper crustal layer present a quite different pattern. As can be seen from Figure (4c) thicknesses of this layer reach up to values of 24km in the central Andean region. Thickness values are in the range of 12 to 20km in the central parts of the continent. Both the northern and southern extremes are characterized by relatively thin upper crust (thicknesses less than 12 km).

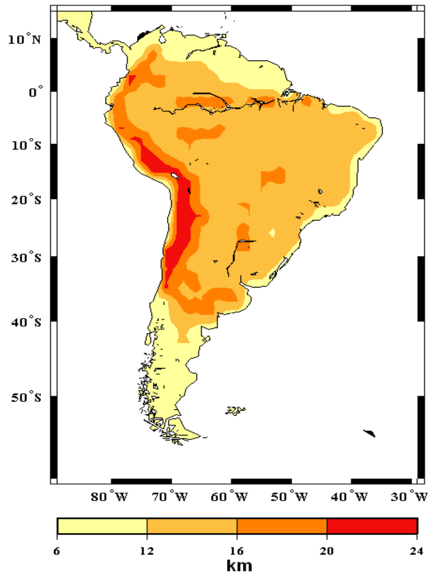

Figure 4c: Thickness of upper crust in South America derived from the data set of Bassin et al (2000).

4. CRUSTAL TEMPERATURES

Vertical distributions of temperatures in the crustal layers were calculated for each of the 2^0 x 2^0 cells. A simple one dimensional heat conduction model, that incorporates the effects of depth-dependent variations in thermal conductivity and radiogenic heat production, was used for this purpose. The relation for temperature (T_i) as a function of depth (z_i) for the ith grid element is:

$$T(z) = T_{0i} + \frac{q_{0i} - A_{0i}\, D_i}{k_i}\, z + \frac{A_{0i}\, D_i^{\,2}}{k_i}\left[1 - e^{-Z_i / D_i}\right] \quad (1)$$

where T_{0i} is the surface temperature, q_{0i} the surface heat flux, A_{0i} radiogenic heat productivity and k_i the thermal conductivity of the ith element. The values of A_{0i} is derived from empirical relations (Cermak et al, 1990) relating crustal seismic velocities with radiogenic heat productivity.

The thermal conductivity values of the sedimentary layers were derived from the heat flow data base. The spatial distributions of basal temperatures of the soft and hard sediment layers and upper crust, calculated using equation (1), are presented in Figures (5a), (5b) and (5c) respectively. Note that temperatures in excess of 80^0C at the base of soft sediments (see Figure 5a) occur only in northern Venezuela, altiplano region and northern Chile. In most of the remaining regions it falls in the range of 40 to 60^0C.

In the case of hard sediments (see Figure 5b) the basal temperatures in excess of 80^0C occur in several localities lying along an arc shaped belt extending from northern Venezuela to central Brazil, passing through southeast Ecuador and Altiplano region of Bolivia. Temperatures of less than 80^0C are found along the eastern parts of the continent.

In the case of upper crust temperature calculations were carried out for an assumed set of thermal conductivity values. Also, effects of temperature dependence of thermal conductivity were ignored. Such procedures represent sources of uncertainty in model results. But the magnitude potential errors involved are likely to be of the same order or even less than the uncertainties associated with the gradient and heat flow values. According to results obtained (see Figure 5c) basal temperatures in excess of 300^0C are found to fall along most of the Andean. Surprisingly the upper crust in the southern cordillera in Chile is characterized by basal temperatures lower than 250^0C. In the eastern parts of the continent basal temperatures in excess of 300^0C are found to occur in the northeastern coastal region of Brazil and also along an east west trending belt between the northern part of the state of Mato Grosso and northern parts of the state of Rio de Janeiro.

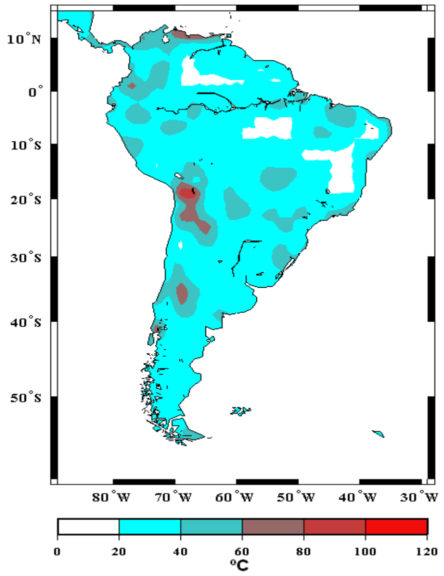

Figure 5a: Temperatures at the base of soft sediment layer.

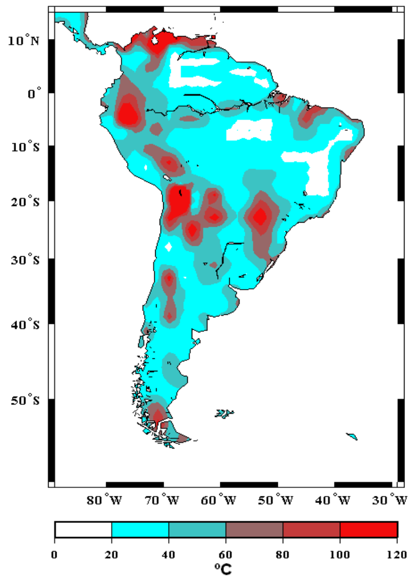

Figure 5b: Temperatures at the base of hard sediment layer.

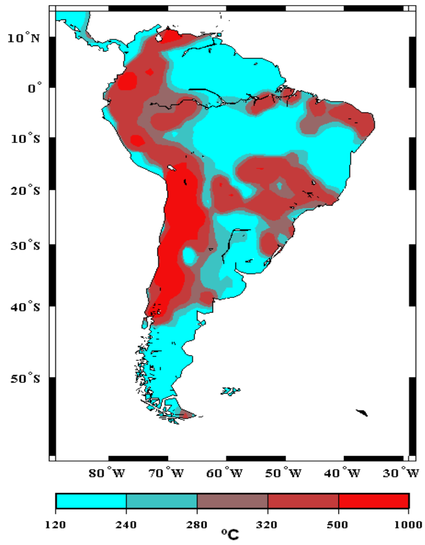

Figure 5c: Temperatures at the base of upper crust.

5. ESTIMATES 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 up to a depth of 10km, the reference temperature value for energy calculations being the surface temperature. The resource base (Q_{RBi}) for the i^{th} cell, of thickness d_i, associated with the temperature distribution given by equation (1), is calculated using the relation:

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

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. The results obtained are presented in Figures (6a), (6b) and (6c) respectively for the soft sediment, hard sediment and upper crustal layers.

In the case of the soft sedimentary layer (see Figure 6a) estimates of resource base fall in the range of 10^{12} to 10^{14}J. Values higher than 10^{13}J are found to occur only in relatively small regions, mainly in the western parts of the continent. It includes northern parts Colombia and Venezuela, northern Peru, the altiplano region of Bolivia and the northwestern parts of Argentina. In the eastern parts of the continent isolated regions with values up to 40TJ occur in several parts of Brazil (southeastern part of the state of Santa Catarina, northern parts of state of Mato Grosso and the states of Ceará and Rio Grande do Norte).

In the case of hard sedimentary layer (see Figure 6b) estimates of resource base fall in the range of 10^{13} to 10^{15}J. Values higher than 10^{14}J are found to occur as a set of discontinuous regions distributed along a semi-circular shaped belt, surrounding the cratônica areas Guiana and Guaporé. The belt seems to start from northern Venezuela and ends up in Parana basin in southeast Brazil, after passing through north-central and south-central parts of Peru, altiplano of Bolivia and eastern Paraguay.

In the case of upper crustal layer (see Figure 6c) estimates of resource base fall in the range of 10^{14} to 10^{16}J. Occurrence of values higher than 10^{15}J is restricted to the central parts of western cordillera, with the highest values in the altiplano region.

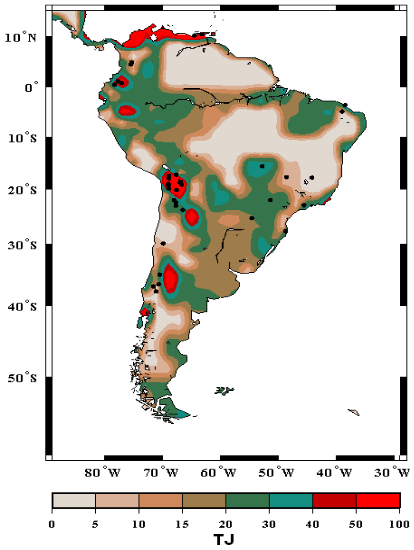

Figure 6a: Resource base for the soft sediment layer. The dots indicate localities of geothermal areas.

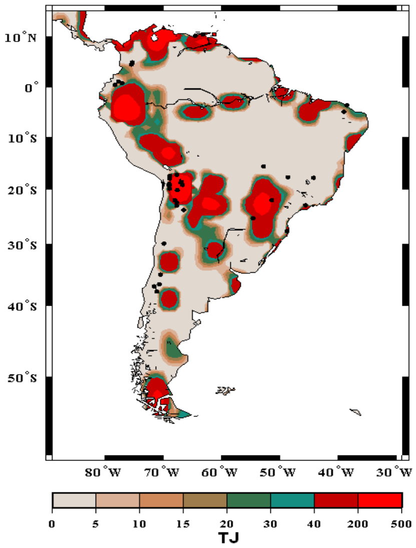

Figure 6b: Resource base for the hard sediment layer. The dots indicate locations of geothermal areas.

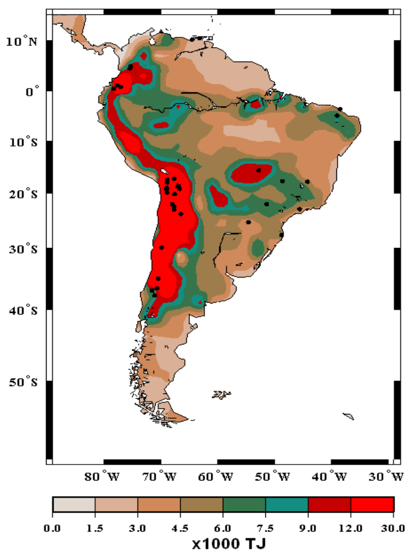

Figure 6c: Resource base for the upper crustal layer. The dots indicate locations of geothermal areas.

5. DISCUSSION AND CONCLUSIONS

Unlike previous studies the results obtained in the present work have lead 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 lead 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.

Another important point emerging from the results of the present work is that high enthalpy resources in the western parts of the continent are almost all of deep crustal origin while low enthalpy resources in the eastern parts of the continent are almost all of shallow crustal origin.

We have provided so far 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. Results of such an attempt are presented in the map of Figure (7). Note that maximum value of the integrated resource base is 10000 TJ. This value is significantly different from that obtained in previous studies.

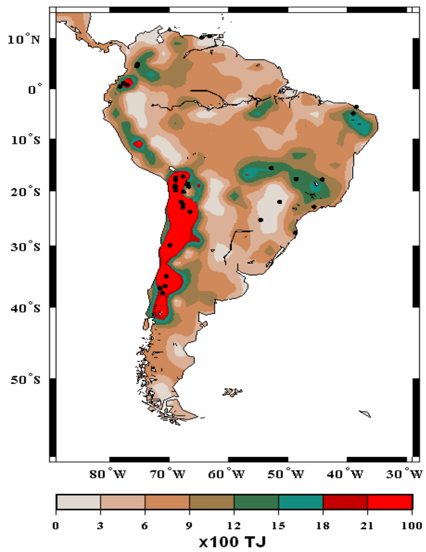

Figure (7) Map of total resource base referred to the maximum depth limit of 3km.

6. ACKNOLEDGEMENTS

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