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Obliteration of Thermal Springs by Lateral flow of Groundwater: Implications for Resource Assessments

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ABSTRACT

Analysis of geothermal characteristics of hydrogeologic provinces of Brazil has identified the existence of an association between the geographic distributions of thermal springs and areas of occurrences of lateral flows of groundwater. Occurrences of thermal springs are found to be rare or altogether absent in regions inferred to have lateral flows of groundwater. This trend is remarkably evident in the sedimentary basins of the Amazon region, in the central parts of the Parnaiba basin and in the west-central parts of the Paraná basin. Results of model simulations indicate that groundwater flows with velocities in excess of few cm/year, along flat-lying aquifers, are potentially capable of masking the occurrences of thermal anomalies. Also, down-flows through distributed recharge zones are found to lead to the development of large regions of relatively low temperatures, capable of suppressing surface manifestations of deep geothermal resources. The observational data sets of temperature gradients and Peclet numbers have been employed outlining advection - convection domains of subsurface strata. The results indicate that advective down flows are capable of opposing thermal buoyancy forces and obliterating upward movements of thermal fluids. Vertical and lateral flows of cold groundwater can also lead to development of large zones of relatively low temperatures, capable of suppressing surface manifestations of deep geothermal resources. Though hydrogeological and geochemical data for the thermal spring systems of Brazil are limited it appears that an understanding of the perturbing effects of lateral flow systems in the subsurface is important in assessment of geothermal resources.

1. INTRODUCTION

Thermal springs are usually considered as natural discharges from subsurface accumulations of geothermal fluids. Thus, studies of the physical and chemical characteristics of thermal springs and their geographic distribution with respect to the main geologic structures form an important part of the initial stages geothermal exploration. Usually site-specific information about the lithologic characteristics of subsurface layers and their respective thermal fields is employed in assessments of geothermal resources associated with thermal springs. Nevertheless, most such procedures ignore the perturbing effects of large-scale subsurface movements of groundwater on the upward migration of thermal fluids. Thermal effects of groundwater flows have been examined in several of the earlier works (Domenico and Palciauskas, 1973; Forster and Smith, 1989; Gosnold, 1990; Ingebritsen et al, 1992; Manga and Kirchner, 2004; among others). Ferguson and Grasby (2011) presented evidences in favor of a significant correlation between spring temperature and flow system geometry and pointed out the relative importance of advection in groundwater flow systems. They also proposed the possibility of a link between basin dimensions and discharge temperature, implying that hydrogeology and structural geology are important in determining the distribution and characteristics of thermal springs.

Recently, Vieira and Hamza (2012) pointed out absence of thermal springs in zones of large-scale lateral movements of groundwater, mainly in Paleozoic sedimentary basins of Brazil. They argued that up flowing hot fluids lose their thermal buoyancy upon mixing with lateral flows of groundwater, and this leads to eventual obliteration of thermal springs at the surface. They also concluded that lateral flows of groundwater have potential for masking thermal anomalies associated with deep geothermal reservoirs. It is clear that assessment of geothermal resources in such basins needs to take into account the perturbing effects of groundwater flows. Similar observations have also been made in other parts of the world, notable examples being the absence of thermal springs in the Gangetic plains and Godavari basin in India (Roy and Gupta, 2012) and in the sedimentary basin of Western Canada (Wright et al, 1994). The present work provides brief summaries of thermal springs and deep groundwater flow systems in the sedimentary basins of Brazil and examines the spatial associations between the two. For purposes of the present work attention is focused on flow systems operating in the Paleozoic interior basins, associated with the hydrogeological provinces. These include sedimentary basins of the Amazon region in the north (Acre, Solimões, Amazonas and Marajó), Parnaiba province in the northeast and Paraná province in the south.

2. OCCURRENCES OF THERMAL SPRINGS IN BRAZIL

According to Hurter et al (1983) and Furumoto (1990) thermal and mineral springs have been identified at nearly over 400 localities in Brazil. Most of the springs have discharge temperatures in the range of 30 to 50^{o}C. In many cases chemical analysis of the spring waters indicate that parts of fluids in the springs originates from deep reservoirs and mixing processes with non-thermal fluids along the up-flow paths are widespread. Hamza et al (2005) reported estimates thermal capacities of the main spring systems, which are calculated as the product of flow rate and estimates of useful temperature difference, these latter ones derived as the difference between out-flow temperatures of the spring and local mean annual ground temperatures. The springs have been classified into four groups depending on the current state of utilization. According to estimates by Hamza et al (2005) the total capacity of low temperature geothermal systems under economic exploitation is 362 MWt, while the annual energy use is estimated to be of the order of 6536 TJ (Tera Joules). 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). According to Hamza and Eston (1983) the geothermal resource base associated with thermal spring systems in Brazil is of the order of 10^{18} Joules. A summary of data on the major thermal spring systems is provided in Table 1.

Table 1 Thermal spring systems in Brazil, with capacity greater than 2 Megawatt Thermal (MWt).

Locality	Coordinates (DD)		Flow Rate	Temperature	Capacity
	Latitude	Longitude	(l/s)	(^{0}C)	(MWt)
Cachoeira Dourada	18.4920	49.4750	139	40	6
Caldas Novas	17.7478	48.6258	333	57	35
Itajá	19.1333	51.6000	400	38	15
Rio Quente	17.7478	48.6258	1667	42	70
General Carneiro	15.7000	52.7667	152	46	10
Águas do Veré	25.8833	52.9167	694	38	23
Piratuba	27.4200	51.7720	194	39	7
Cornélio Procópio	23.1747	53.6469	14	48	2
Araçatuba	21.2090	50.4330	417	48	31
Fernandópolis	22.8400	50.2460	14	59	2
Jales	20.2667	50.5500	14	61	2
Paraguaçu Paulista	22.4130	50.5760	14	48	2
Presidente Epitácio	21.7630	52.1160	28	78	6
Presidente Prudente	22.1260	51.3890	56	63	8
São José do Rio Preto	20.8156	49.3858	28	45	2
Taubaté	23.0250	45.5586	28	48	2
Total					223

The flow rates of some of the spring systems are relatively large. A well-known case is the geothermal area of Rio Quente (State of Goiás, in central Brazil) where the flow rate of thermal waters is estimated to be approximately 6000m^3/h. In the nearby municipality of Caldas Novas, substantial quantities of thermal waters are extracted by pumping wells. The State of Mato Grosso, to the west of the State of Goiás, is known for widespread occurrence of thermal springs, along an east west trending belt in its central parts. Thermal spring systems are also abundant in the southern parts of Brazil, mainly in the State of Santa Catarina.

The spatial association between thermal springs and regional hydrogeologic features is illustrated in Figure 1. In this figure, areas with dark brown shading denote the extent of major Paleozoic sedimentary basins, while orange shading denote areas where sedimentary cover is thin or altogether absent. As expected, thermal springs are absent in most of the cratonic areas, such as Guiana craton in the north, Guaporé craton in the central region and São Francisco craton in the east. But the most outstanding feature is the occurrences of thermal springs at the border regions of sedimentary basins. It is remarkable that thermal springs are absent in the interior parts of the basins, indicated with blue shading in Figure 1. A prime example is the Amazon region, which is practically devoid of thermal springs, the only cases reported to date being small isolated occurrences at Xapury, Urucurituba, Evere, Maracanã and Itaituba (Waring et al, 1965; Hurter, et al, 1983), all of them occurring at the border zones.

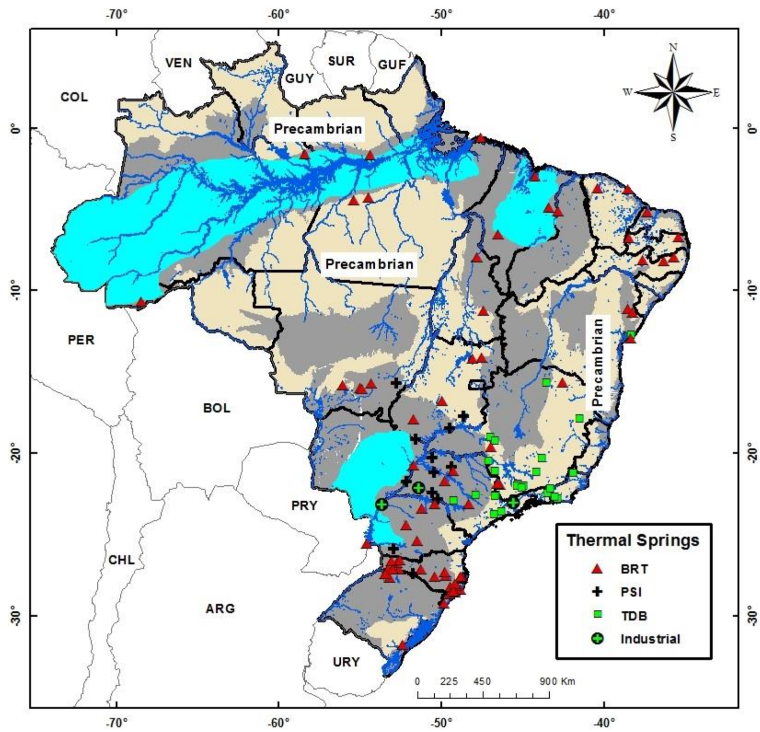

Fig. 1 Map illustrating simplified regional geologic features and distribution of thermal spring systems in Brazil. The symbols (triangles, crosses and squares) indicate current modes of utilization of these thermal spring systems. TDB – Therapeutic Drinking and bathing; PSI – Potential for space heating and industrial use; BRT – Bathing, Recreation and Tourism.

Similar conditions prevail in the interior parts of the Parnaíba and Paraná basins. Thermal springs in the Parnaiba basin are also found to be located along the border zones (at Rosário, Caxias and Boa Vista). In the Paraná basin, thermal springs are absent in the west-central parts, but a number of springs are located in its eastern parts. However, this part of Paraná basin is known to have a large network of sub-vertical mafic dikes, which cut across the deep sedimentary strata and which extend into the basement complex. These dikes were emplaced during late Cretaceous times and acted as conduits of flood basalts, which cover much of the central parts of the basin. Results of hydrogeologic studies indicate that the dikes act as impermeable barriers against deep lateral flows of groundwater in this part of the basin. It is quite likely that thermal waters originating from deeper strata in this region are forced upwards and appear as thermal springs. Such barriers are absent in basins of the Amazon region and in the Parnaíba basin. Given the similarities in the tectonic evolution and geothermal fields of basement structures of these regions, it seems unlikely that such features in the geographic distribution of thermal springs arise because of mere chance coincidence. Hence, we consider here the possibility of the existence of a powerful heat sink mechanism in the central parts of these sedimentary basins, which inhibits the occurrence of thermal springs.

3. GROUNDWATER FLOWS IN SEDIMENTARY BASINS OF BRAZIL

Vieira and Hamza (2012) reported results of an analysis of geothermal data from deep oil wells in the Paleozoic interior basins (Amazon region, Paraná and Parnaiba). These studies make use mainly of bottom-hole temperature (BHT) measurements in oil wells in the basins of the Amazon region in the north, Parnaíba basin in the northeast and Paraná basin in the south. Analysis of these data sets revealed non-linear features in vertical temperature distributions indicative of the occurrence of deep groundwater flows (Pimentel and Hamza, 2011; 2012). Subsequently procedures proposed by Lu and Ge (1996) and Reiter (2001) were employed in determining velocities and directions of deep regional groundwater flow systems, in both the horizontal and vertical directions (Pimentel and Hamza, 2014).

The directions of lateral flows of groundwater in the basins of the Amazon region as well as the Parnaíba and Paraná basins are indicated as blue shaded areas in the maps of Figures 2a, 2b and 2c, respectively. In the case of the Amazon region (Figure 2a), the inferred direction of the lateral flow is from west to east, following roughly the same course as the Amazon River. The flow path, within the Brazilian territory, extends all the way from the foothills of the Andean mountains to the Atlantic Ocean. The total estimated length of the flow path passing through the basins of Acre, Solimões, Amazonas and Marajó is more than 5000 km, with widths varying from 200 to 300 km. The discharge zone of this flow system is believed to be situated in the submerged continental margin to the east of Marajó basin. This is not altogether surprising as submarine groundwater discharge systems have been identified in several parts of continental margins, both in the northern as well as the southern hemisphere (Taniguchi et al, 2002).

In the case of Parnaiba basin (Figure 2b), the inferred direction of flow is from south to north, following roughly the same course as the Parnaiba River. The discharge zone of this flow system is believed to be situated along the submerged continental margin to the north of the basin. In the case of Paraná basin (Figure 2c), the inferred direction of flow is from northeast to southwest, following roughly the course of the Paraná River in southern Brazil. The estimated lengths of the flow paths for each of these basins are in the range of 500 to 700 km, with widths varying from 200 to 300 km. The discharge zone has not been mapped in this case, as the study has been limited to the Brazilian territory. However, Paraná basin is contiguous with the Chacos basin to the south, which in turn is connected to the continental margin in northern Argentina.

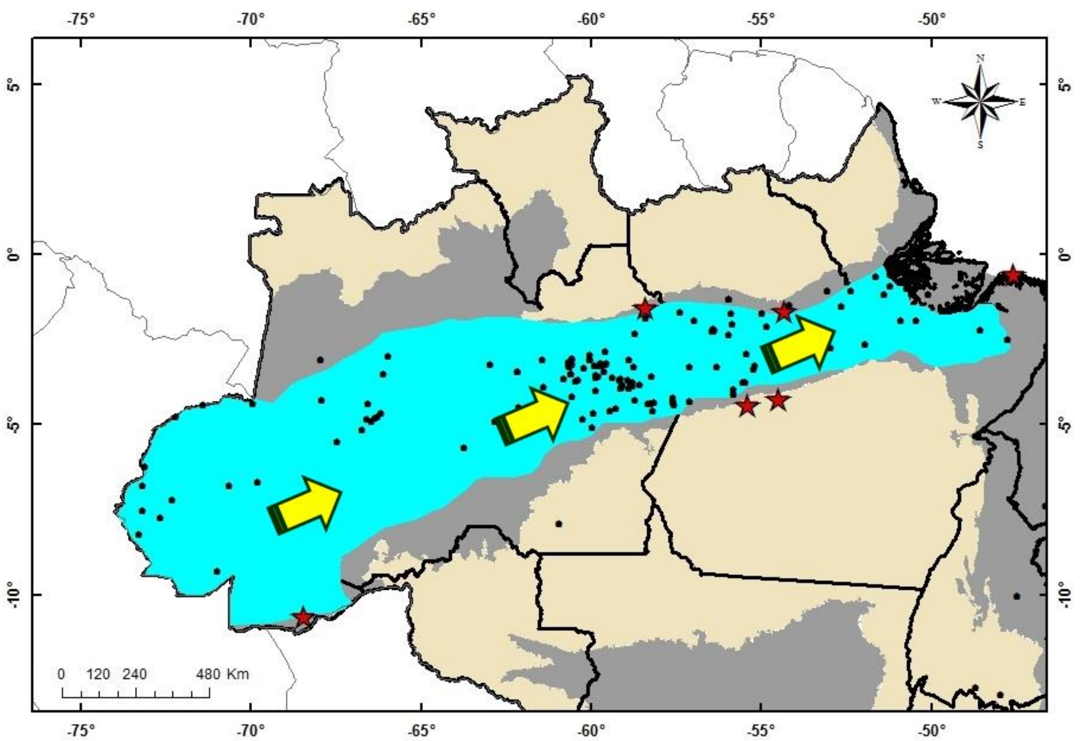

Fig. 2a Region of lateral flow of ground water (blue shaded area) in the Paleozoic sedimentary basins of the Amazon region. The arrows indicate inferred direction of lateral flow. The dots indicate sites of geothermal measurements, while the star symbols indicate localities of thermal springs.

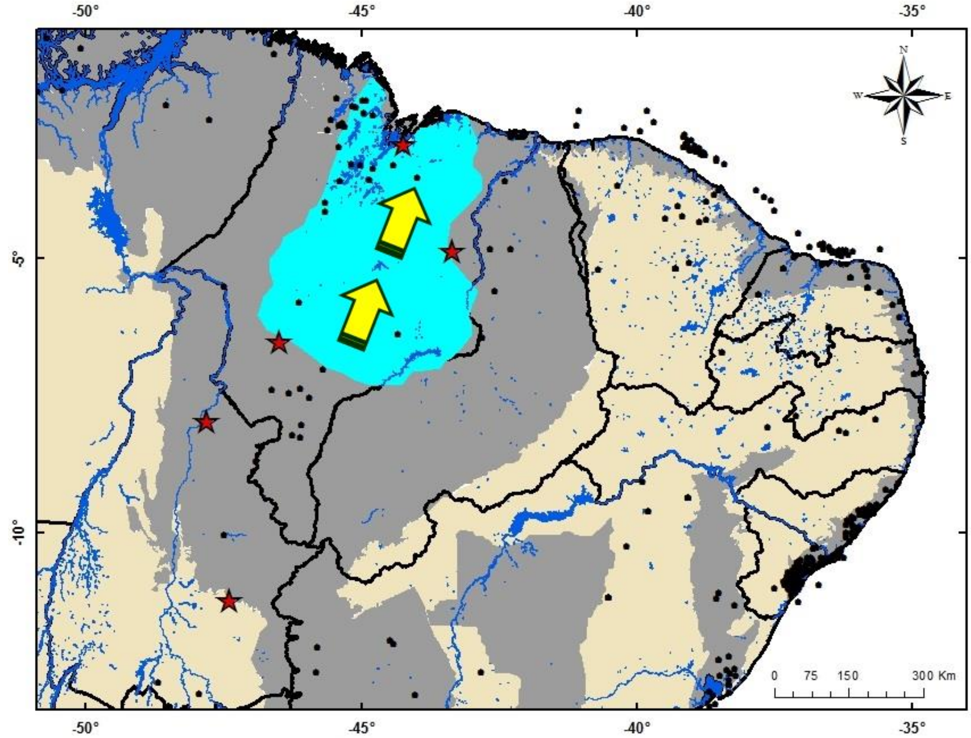

Fig. 2b Region of lateral flow of ground water (blue shaded area) in the Parnaiba basin. The arrows indicate inferred direction of lateral flow. The dots indicate sites of geothermal measurements, while the star symbols indicate localities of thermal springs.

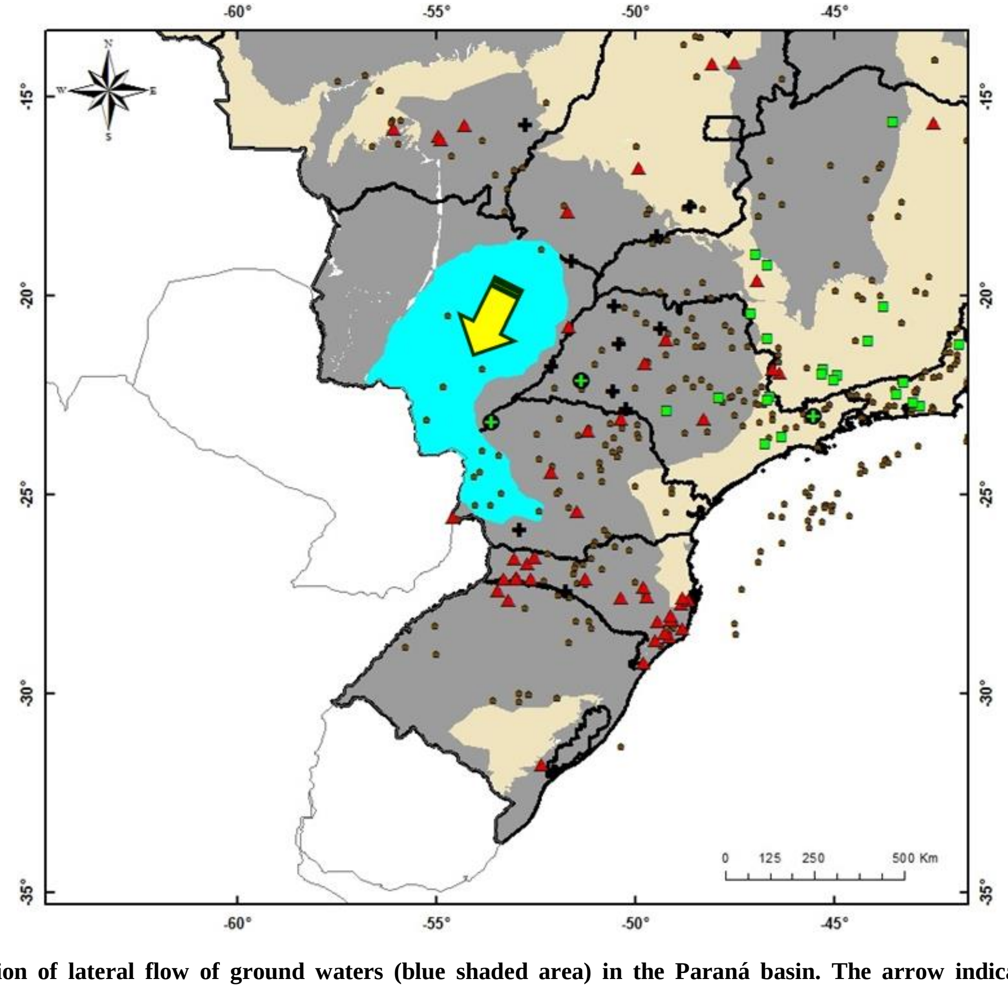

Fig. 2c Region of lateral flow of ground waters (blue shaded area) in the Paraná basin. The arrow indicates inferred direction of lateral flow. The dots indicate sites of geothermal measurements, while the symbols (triangles, squares and crosses) indicate localities of thermal springs.

A remarkable feature of the results for basins of the Amazon region (namely Acre, Solimões, Amazonas and Marajó) and the northern region (Barreirinhas) has been the indication of of the presence of large-scale vertical down flow systems of groundwater. In most cases, the down flow velocities were found to be of the order of 10^{-9} m/s while horizontal velocities are significantly higher, of the order of 10^{-8} m/s. Results obtained for the data sets from the Parnaíba and Paraná basins revealed a more complex pattern, with both up flows and down flows. A brief summary of the results obtained for groundwater flow velocities in the main Paleozoic basins of Brazil is presented in Table 2.

Table 2 Estimates vertical and horizontal velocities and flow parameters for the different depth ranges in the basins of the Amazon region. The last column provides estimates of permeability contrast, based on flow velocities of lower relative to upper layers.

Basin	Depth Range (m)	Velocity (10^{-9}m/s)		Permeability Contrast
		Vertical	Horizontal	
Acre	2204-3747	1.4	49	35
Solimões	2087-3066	1.1	44	40
Amazonas	1867-3074	1.1	33	30
Marajó	1910-3762	0.9	30	33
Barreirinhas	1874-2842	0.9	22	24
Parnaiba	786-2856	1.3	60	46
Paraná	1396-2792	1.0	40	40

4. INTERACTIONS BETWEEN LATERAL FLOW OF GROUNDWATER AND UP-FLOW OF THERMAL WATERS

We consider here the interaction between the thermal field associated with upwelling hot fluids (originating from a deep seated reservoir) with that of the vertical advective movements of groundwater in the confining layer (aquitard) overlying the sub-horizontal aquifer. The purpose is to explore the interaction of flow systems under the combined action of advection and thermal convection. Two different modes of interaction may occur depending upon the direction of groundwater flow. In case of down-flow of groundwater, the buoyancy of the upwelling fluids must overcome the advective down-flow, before reaching the surface and contribute to thermal springs. In case of up-flow of groundwater, as would be the case in a discharge zone, the buoyancy of the upwelling fluids act in the same direction as that of the advective up-flow. Consequently, advection supports up-flow of thermal fluids and contributes to thermal springs. A schematic illustration of these two cases is presented in the two panels of Figure 3, where the arrows in blue color indicate directions of advective flows while those in red color indicate up-flows of thermal fluids. Note that the upper panel refers to the case where advection opposes thermal convection. The lower panel refers to the case where advection and convection act in the same direction.

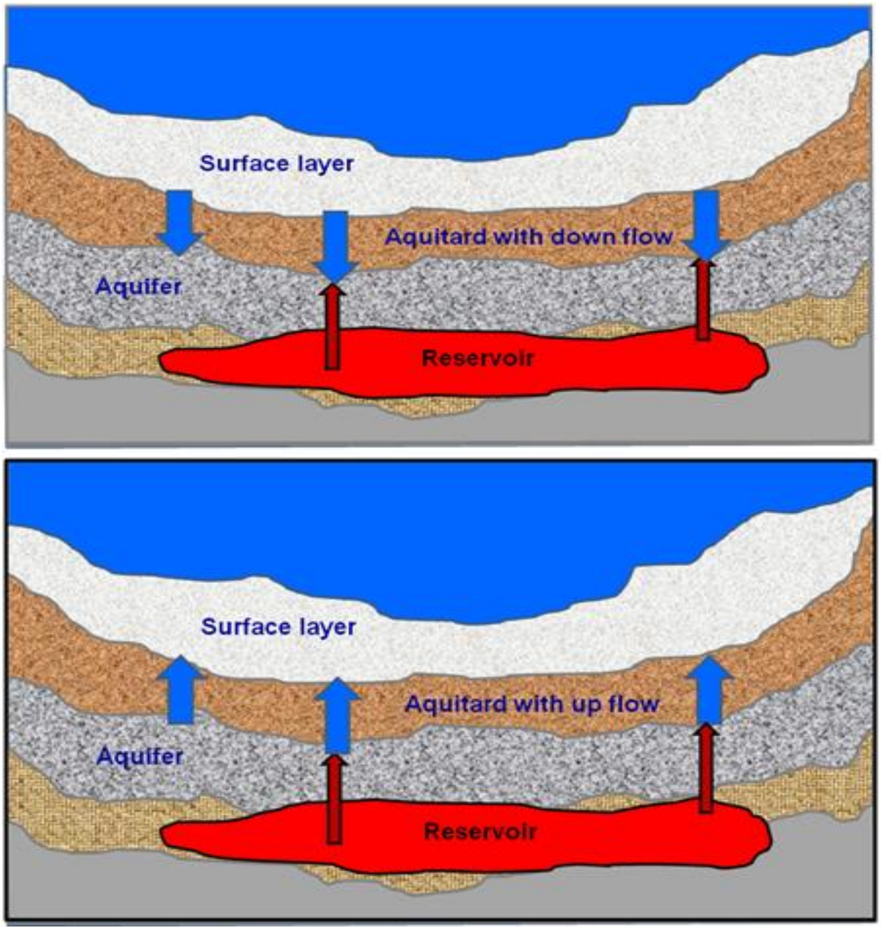

Fig. 3 Schematic illustrations of the two modes of interaction between up-flow of thermal fluids and advective flow of groundwater in the confining layer (aquitard) overlying the aquifer.

The nature of interaction of groundwater and thermal waters is better understood by considering the Peclet and Rayleigh numbers of the flow systems. Zhao et al (1999) has considered cases where overall energy transfer takes place by both convection and advection. In such cases, it is convenient to explore the nature of correlations between the dimensionless Peclet number and the critical Rayleigh number. It is evident that, the critical Rayleigh number for the up-flow systems is not constant, but varies with the upward flow velocity, expressed in terms of the Peclet number. The relation derived by Zhao et al (2008) serves as a convenient starting point. It is given as:

$$R_a = \frac{366\ C_{11}\ C_{22}}{17\left(k_1^*\right)^2 C_{21}} \qquad (1)$$

where the terms C11, C22 and C21 are given by the relations:

$$C_{11} = -\left[\frac{1}{3} + \frac{2}{15}\left(k_1^*\right)^2\right] \qquad (2)$$

$$C_{22} = -\left[\frac{1}{9} + \frac{1}{3}\left(k_1^*\right)^2 - \frac{1}{50} Pe\right] \qquad (3)$$

$$C_{21} = \frac{1}{p_e^{8}}\left[e^{p_e}\left(\frac{1}{2} p_e^{6} - 2 p_e^{5} + 3 p_e^{4} + 12 p_e^{3} - 108 p_e^{2} + 306 p_e - 504\right) + \left(504 + 144 p_e + \frac{1}{5} p_e^{5} + \frac{1}{5} p_e^{6}\right)\right] \qquad (4)$$

The quantity K_1* is the dimensionless wave number (product of K_1, the wave number in the x direction, and H) and C_{22} is a polynomial trial function. Referring to equations (1 to 4) it is simple to note that, the critical Rayleigh number for up flow systems is not a constant, but varies with the upward flow velocity, expressed in terms of the Peclet number. Zhao et al (2008) presented results of numerical simulations for Peclet numbers in the range of zero to (50/9). The main conclusion is that advective forces acting in the upward direction promotes convective fluid flows. Thus even small convective thermal gradients can lead to uprising plumes and hence formation of thermal springs. In the present work, we argue that this analysis may also be extended to down flow systems. In the domain of down flows, Peclet numbers are negative, as per the sign convention used by Zhao et al (2008). The proposed extrapolation is based on the assumption that net changes in temperature gradients arising from differences in advective and convective forces have asymptotic limits. This is a reasonable since thermal buoyancy will normally have a higher finite limiting value compared with that of advection. Hence, the differences in the limiting values approach asymptotic limits. The parameter values of the curve representing such variations in gradients has been adjusted such that it coincides with the polynomial fit for the benchmark problem, in the interval of $0 < Pe < 5$, considered by Zhao et al (2008). The results obtained are illustrated in Figure 4, where we have used, instead of the critical Rayleigh numbers, the corresponding values of critical convective thermal gradients of the flow system.

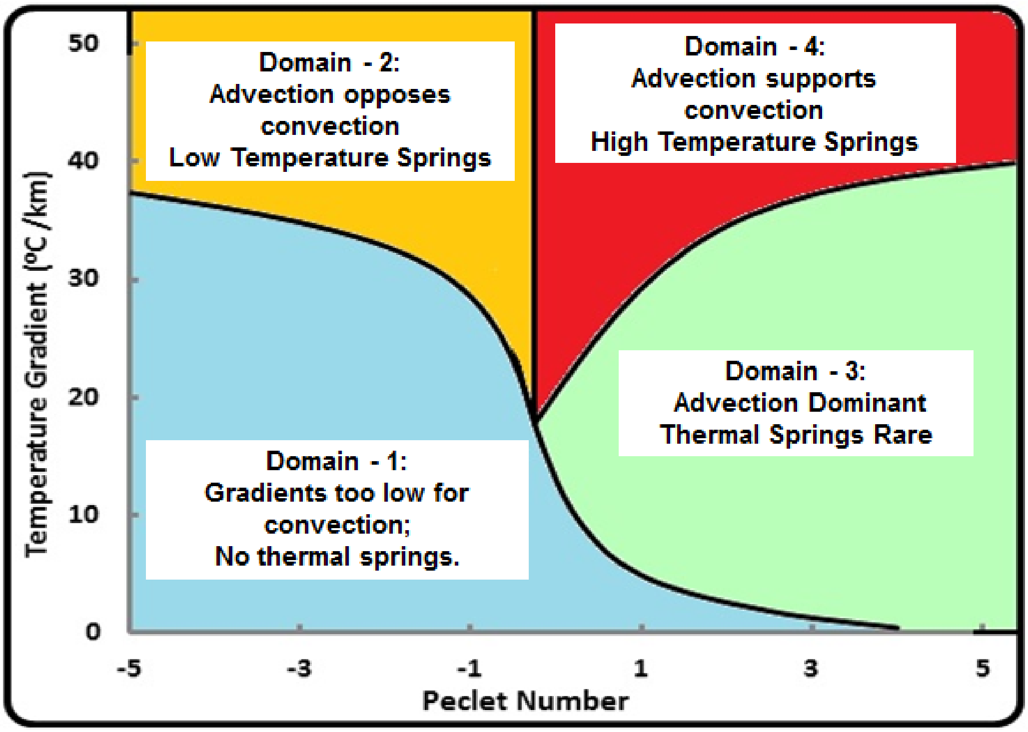

Fig. 4 Heat and mass transfer domains (1, 2, 3 and 4) in the relation between critical thermal gradients and Peclet numbers of groundwater circulation systems. See text for details.

The vertical line in this figure separates regions of down-flows and up-flows by advection. The lower part of the curve in black color, on the right hand side of the vertical line, illustrate the relation between critical temperature gradients and Peclet number for up flow systems, as proposed by Zhao et al (2008). The upper part of the curve in black color, on the left hand side of the vertical line, illustrate the relation between critical gradients and Peclet number for down flow systems, as proposed by Vieira et al (2014). The upper curve on the right hand side is actually a mirror image of the curve on the left hand side. The upper limit of the critical gradients has been set to 50°C/km, which is the maximum value encountered in sedimentary basins of Brazil.

The conjugation of the curves for up-flows and down-flows allow us to identify distinctly different domains of heat and mass transfer in regions of groundwater flows. For example, the region where Rayleigh number falls below its critical value is designated as domain – 1. It corresponds to the region where thermal buoyancy forces cannot overcome the internal resistance against upflow. Peclet numbers are mostly negative and advection opposes thermal buoyancy. This additional resistance against upward movements of thermal waters leads to severe obliteration of thermal springs in this part of domain - 1.

The region overlying the curve of critical gradients may be considered as composed of several sub-domains, depending on the action of advective flows. For example, in the region to the left of the vertical line and overlying the curve of critical gradients, occurrence of thermal springs depends on the force balance between thermal buoyancy forces and advection. This region has been designated as domain 2 (shaded yellow color) in Figure 4.

In the region to the right of the vertical line, the Peclet numbers are positive and the advective forces act in the same direction as that of the thermal buoyancy forces. This condition promotes upflow, but the ensuing mixture of thermal and groundwaters leads to lower than normal out-flow temperatures for thermal springs. Two sub-domains can be envisaged in this case, depending on whether mass flux of groundwaters is higher or lower than that of thermal waters. These are indicated as sub-domains 3 (shaded green color) and 4 (shaded red color) respectively. In sub-domain 3 advection dominates the mixing process, while in sub-domain 4 convection dominates the mixing process. The separation between domains 3 and 4 is indicated by a dashed curve representing the relative contributions of mass flows of thermal waters and groundwaters in the mixing process. The origin of this curve is set at the point where Peclet number is zero and where the corresponding gradient value is approximately 14°C/km.

Within each of these sub-domains, the cooling effect of mixing between cold and thermal waters is likely to be less intense at low Peclet numbers and vice-versa. For example, sub-domain 1 represents the region where advection lowers significantly temperatures of mixed fluids, even when crustal gradients are relatively high. On the other hand, sub-domain 4 represents the region where temperatures of mixed fluids are likely to be relatively high even when crustal gradients are low. Similar considerations also apply to sub-domains 2 and 3.

5. PECLET-RAYLEIGH DOMAINS OF SUBSURFACE FLOWS IN SEDIMENTARY BASINS OF BRAZIL

The results of model fits to observational data, discussed in section 3, may now be used for exploring the nature of Peclet-Rayleigh relations in the basins of Amazon, Parnaiba and Paraná. Consider for example the results for the Amazon region, illustrated in Figure 5. The geothermal gradients are in the range of 12 to 29°C/km while the Peclet numbers are in the range of -2 to 0. The Pe-Ra domain corresponding to these values is located in the lower parts of the region to the left of the curve for critical gradients. This corresponds to domain–1 of Figure 4, implying that occurrences of thermal springs are unlikely in the Amazon region. As pointed out by Pimentel and Hamza (2012) no evidences were found for up-flow systems in the Amazon region. It implies that thermal springs are unlikely in the upper parts of the Amazon basins.

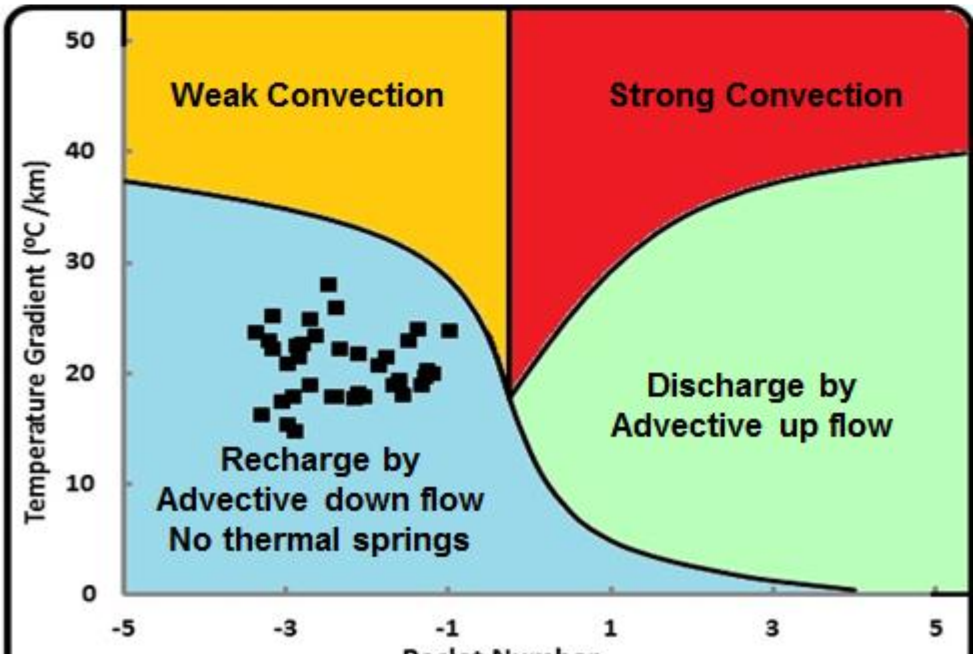

Fig. 5 Relation between thermal gradients with Peclet numbers for the Amazon region. The square symbols indicate observational data. See text for details.

In the case of the Parnaiba basin, illustrated in Figure 6, the thermal gradients are in the range of 15 to 32°C/km, but Peclet numbers are found to have values ranging from -5 to +4. The observational data fall in domains on either side of the curve for critical gradients, pointing to the existence of groundwater flow systems with recharge as well as discharge. The central parts of this basin are characterized by down-flow systems. According to results reported by Pimentel and Hamza (2014) up-flow systems identified in this basin are located in regions of large-scale fault systems. These are localities with potential for occurrence of thermal springs.

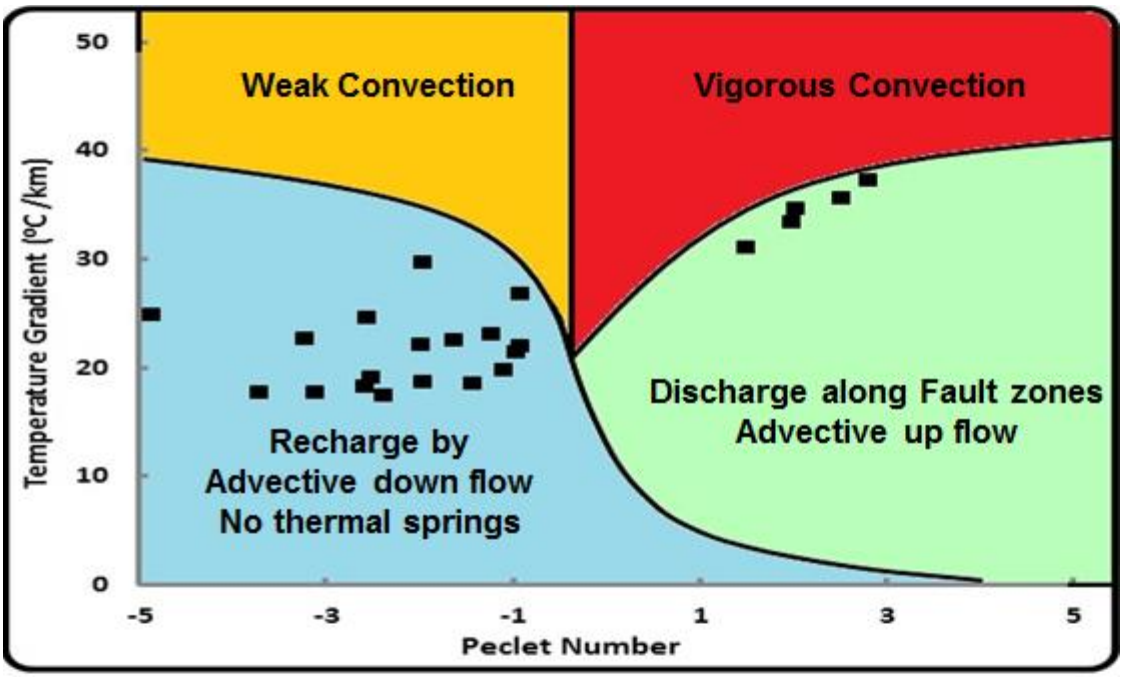

Fig. 6 Relation between thermal gradients and Peclet numbers for the Parnaiba basin. The square symbols indicate observational data. See text for details.

In the case of Paraná basin, illustrated in Figure 7, the thermal gradients are in the range of 15 to 40°C/km and the Peclet numbers are in the range of -5 to +3. Thus the observational data fall on either side of the curve for critical gradients, indicating the existence of groundwater flow systems associated with recharge as well as discharge. The eastern parts of this basin are characterized by the presence of down-flow systems, while several regions surrounding the central parts are characterized by the presence of up-flow systems. The presence of observational data in all four domains is indication that the occurrence of thermal springs is likely to be widespread.

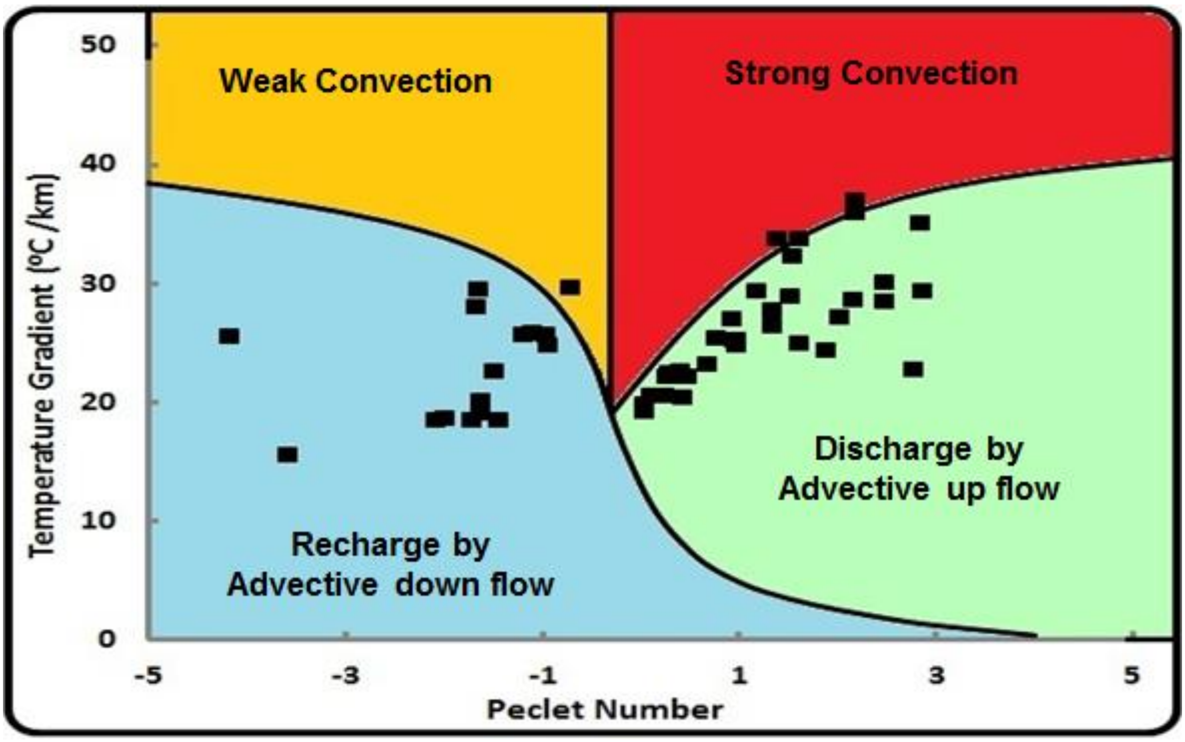

Fig. 7 Relation between thermal gradients and Peclet numbers for the Paraná Basin. The square symbols indicate observational data. See text for details.

6 IMPLICATIONS FOR RESOURCE ASSESSMENTS

Assessments of geothermal resources are usually carried out without consideration of subsurface perturbations in the temperature fields induced by groundwater flows. In such studies, deep temperatures are estimated based on extrapolations of gradient values at shallow depths. Extrapolations based on low gradient values in the top part of the recharge zone can lead to underestimates of temperatures at deeper depth intervals. An immediate consequence is the tendency to underestimate excess temperatures employed in assessments of geothermal resources. Consider for example the schematic temperature distributions in a basin and in the underlying basement rocks, both having constant thermal conductivity values, illustrated in Figure 8.

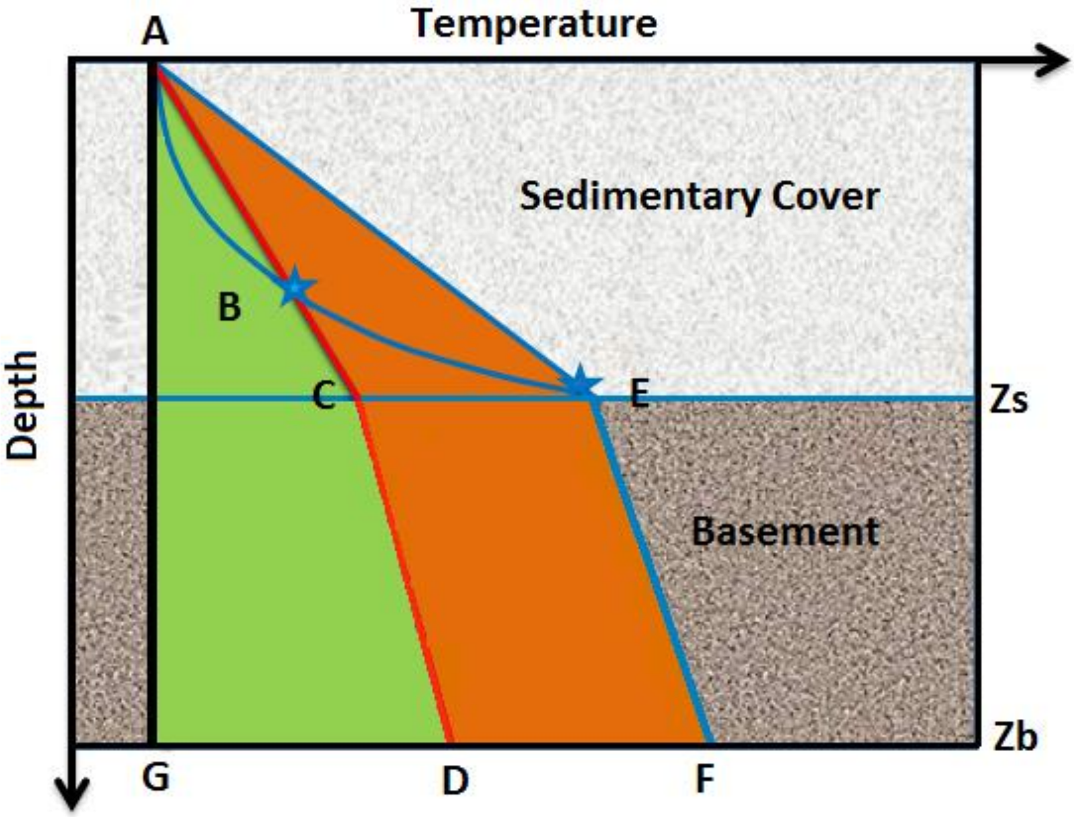

Fig. 8 Schematic illustration of geotherm based on single-point bottom-hole temperatures, in a medium with down-flow of groundwater (Adapted from Pimentel and Hamza, 2014).

The curve ABE in this figure represents the geotherm in the down-flow zone, while line AE is the apparent geotherm for the case in which fluid flow is absent. Linear extrapolation of temperatures based on BHT data at point B, without consideration of fluid flow effects, would lead to geotherm ABCD. Excess temperatures based on the geotherm ABCD lead to estimates of the geothermal resource base related to area of polygon ABCDGA, while the correct one for resource assessment is ABEF. The resource base associated with the polygon EFDCB represents the part that has not been taken into consideration in the conventional interpretation.

7 EXCESS TEMPERATURES ASSOCIATED WITH RESOURCES

The resource base calculations of the present work have been carried out following the methodology proposed in earlier studies. The resource base (RB) is considered as the excess thermal energy in the layer up to a depth of 6 km, the reference temperature value for resource calculations being the mean annual surface temperature. Recoverable resource (RR) is 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, values of porosity and permeability of most common rocks decrease with depth, which imply a corresponding decrease in quantity of circulating fluids in deeper levels. The nature of opposing roles of temperature and porosity variations with depth have been taken into consideration in estimating recoverable resources Numerical simulations with representative values of the main parameters indicate that maximum value of recoverable resource occurs in the depth range of 2500 to 3500 meters. Hence, for purposes of the present work, the estimates of resource base and recoverable resources have been set to a reference depth limit of 3 km. Mean values of porosity adopted for the main rock types are 0.25 (Soft sediments), 0.15 (Hard Sediments), 0.1 (Fracture zones) and 0.05 (Igneous and Metamorphic rocks).
The estimates of excess temperatures associated with geothermal resources for Brazil are based on data acquired in 930 localities. These include results of incremental temperature logs (CVL) and underground mine measurements (MGT) at 109 sites and bottom-hole temperature measurements (BHT) at 301 sites (Hamza and Muñoz, 1996; Hamza et al, 2005). These data sets are derived from compilations discussed in earlier works. Also included are data derived from results of geochemical methods (GCL) for 45 sites and values based on the empirical heat flow – age relation for 131 sites. Most of the data come from southeastern and northeastern parts, while the data density is poor in the north and northwestern parts. The mean value of resource base per unit area is 178 GJ while the recoverable part of this resource base is estimated to be 10 GJ (Vieira and Hamza, 2014).

The maps in the left and right panels of Figure 9 illustrate the distribution of excess temperatures associated with resources at depths of 3 km and 6 km respectively. Note that temperatures in excess of 90 ^{o}C at 3 km depth occur in several parts of southern and northeast Brazil. The cratonic areas in eastern, western and northern parts are characterized by relatively lower temperatures. A similar trend can also be seen in the distribution of high temperature resources at depths of 6 km, illustrated in the right panel of Figure 9.

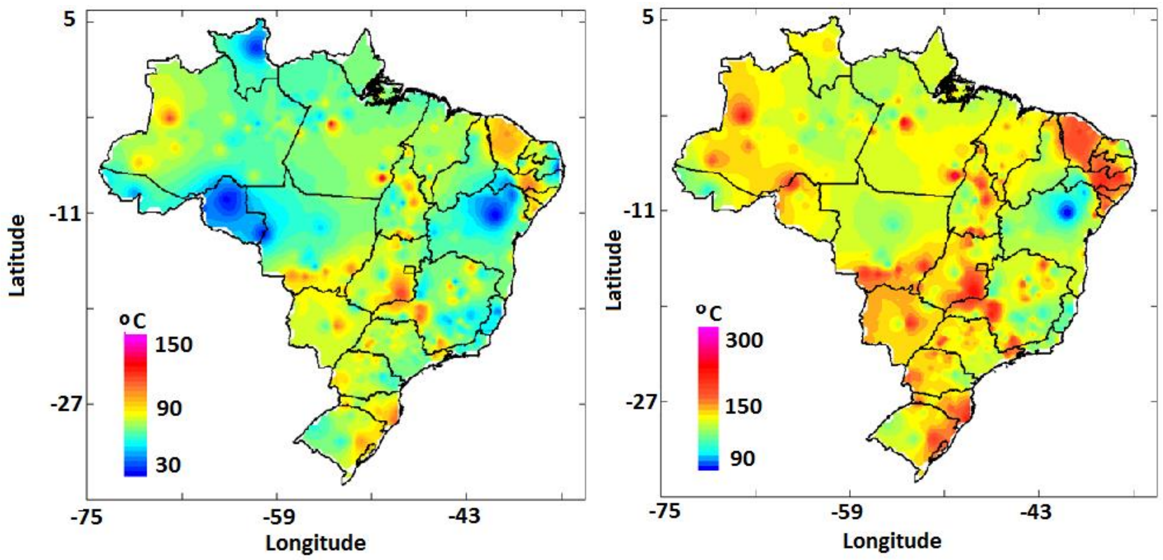

Fig. 9 Distributions of excess temperatures of geothermal resources at depths of 3 km (left panel) and 6 km (right panel).

6 DISCUSSION AND CONCLUSIONS

Analysis of geothermal and hydrogeologic characteristics of Paleozoic Interior basins of Brazil has identified the existence of an association between the geographic distributions of thermal springs and areas of occurrences of lateral flows of groundwater. Specifically, thermal springs are found to be absent in regions inferred to have lateral flows of groundwater.

Analysis of Peclet - Rayleigh domains of flow systems indicate that advective down-flow movements in the overlying layers may lower the temperatures of up-flowing thermal fluids by mixing. The observational data sets of temperature gradients and Peclet numbers have been employed outlining advection - convection domains of subsurface strata in the basins of Amazon, Parnaíba and Paraná regions. Results obtained indicate that thermal buoyancy forces are incapable of overcoming those associated with advective flows in basins of the Amazon region. Similar conditions are also found to prevail in the central parts of the Parnaíba basin and west-central parts of Paraná basin. We conclude that vertical and lateral flows of cold groundwater can lead to development of large zones of relatively low temperatures, capable of suppressing surface manifestations of deep geothermal resources. Analysis of Peclet - Rayleigh domains of flow systems indicate that advective down-flow movements in the overlying layers are also capable of obliterating up-flows of thermal fluids.

Temperatures associated with recoverable resources are significant along central parts of Amazon basins in the north, Parnaiba basin in the northeast and southwestern parts of Paraná basin in the south. Note that absence of sediment cover has led to low values of recoverable resources in northeast Brazil, even though temperatures associated with resource base is high.

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