Indications of Spatial Associations between Deep-seated Groundwater Flow systems and Thermal Springs in Paleozoic Sedimentary Basins of Brazil

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Abstract

We present evidences indicative of the existence of spatial associations between deep lateral flow systems of groundwater and geographic distributions of thermal springs in several of the Paleozoic interior basins of Brazil. Specifically, thermal springs are found to be absent in regions inferred to have deep seated lateral flows of groundwater. This trend is remarkably evident in the basins of the Amazon region, in the central parts of the Parnaiba basin and in the west-central parts of the Paraná basin. We also report progress obtained in model studies of processes responsible for mutual exclusion of regions of thermal springs and lateral flows of groundwater. Results of numerical simulations indicate that lateral flows are potentially capable of masking the occurrences of thermal anomalies. Also, lateral flows lead to development of large low temperatures zones, capable of suppressing surface manifestations of deep geothermal resources. Analysis of Peclet - Rayleigh domains of flow systems indicate that lateral movements are capable of obliterating the effects of thermal buoyancy. We conclude that an understanding of the perturbing effects of subsurface flow systems is important in assessment of geothermal resources.

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 lithological 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.

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.

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. The map of Figure (1) outlines of the main hydrogeological provinces.

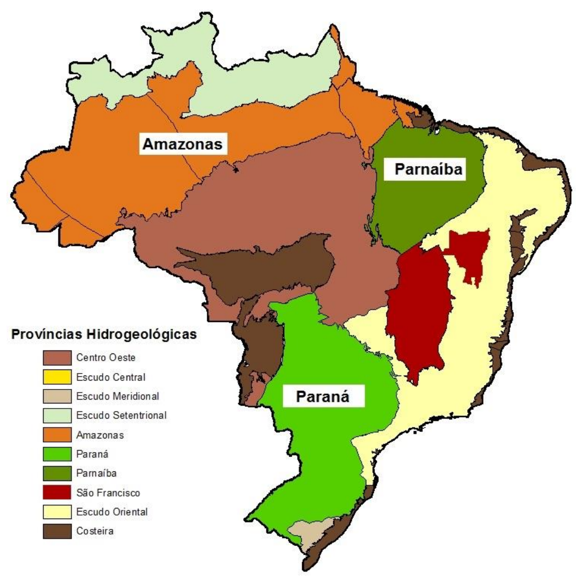

Figure (1) the main hydrogeological provinces.

Occurrences of Thermal Springs in Brazil

According to compilations carried out by Hurter et al (1983) and Furumoto (1990), thermal and mineral springs have been identified at nearly over 400 localities in Brazil. In many cases, individual springs occurring in nearby localities have been given different names, but these actually belong to the same out flow system. Hence, the actual number of spring systems is no more than 100. Most of them are located in the southern, central and northeastern regions. Occurrences of thermal springs are practically absent in most of the cratonic shield areas, such as Guiana craton in the north, Guaporé craton in central parts and São Francisco craton in the eastern parts. This is not altogether surprising, as the crustal temperature gradients in cratonic areas are relatively lower, a consequence of the lower than normal heat flow values in Precambrian shields. The localities of main thermal spring systems are indicated in the map of Figure (2).

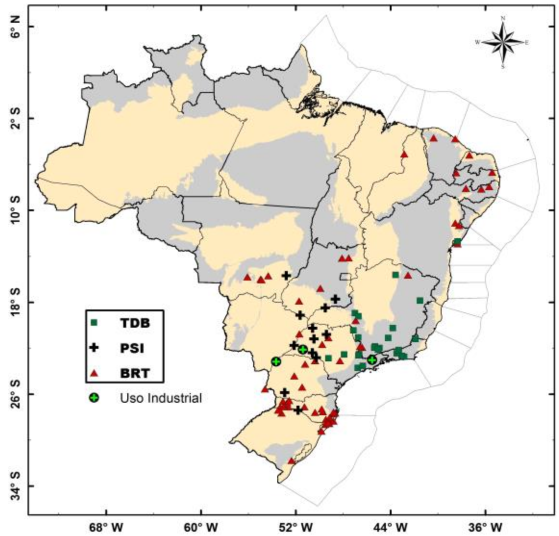

Figure (2) Main thermal spring systems in Brazil and modes of utilization. TDB – Therapeutic Drinking and bathing; PSI – Potential for space heating and industrial use; BRT – Bathing, Recreation and Tourism.

Vertical and Lateral Flows of Groundwater

Pimentel and Hamza (2012) and Vieira and Hamza (2012) have reported progress obtained in analysis of bottom-hole temperature data from deep oil wells in the Paleozoic interior basins (Amazon region, Paraná and Parnaiba). These studies have been successful in identifying non-linear features in vertical distribution of temperatures in several regions, induced by advection heat transfer associated with deep groundwater flows. In most cases, the directions of such flows are found to be downward, indicative of the operation of regional scale recharge systems. Vertical velocities of subsurface fluid flows, calculated from model fits to observational data, are found to fall in the range of 10^{-8} to 10^{-9} m/s.

Occurrences of down flows of groundwater over areas with dimensions of the order of hundreds of kilometers imply that the recharge systems are distributed. Theoretical and practical aspects of distributed recharge systems have been discussed in the earlier works of Freeze and Witherspoon (1966), Lawson (1971) and Sanford (2002). We conclude that the presence of distributed recharge systems operating on regional scales is a characteristic hydrogeologic feature of Paleozoic sedimentary basins, considered in the present work. Similar recharge systems have also been identified in other parts of the world, a notable example being the sedimentary basins of Western Canada (Wright et al, 1994).

Pimentel and Hamza (2012) argued that such extensive recharge movements are possible only in the presence of regional scale lateral flows in the basal parts of sedimentary basins. The reasoning is that vertical down flows at large depths can hardly continue through the relatively impermeable basement rocks. Consequently, down flowing waters of recharge zones changes the direction at deeper levels and eventually end up as lateral flows in the basal parts of sedimentary basins. Studies of groundwater flows at shallow depths in many regions of Brazil indicate that the directions of subsurface hydraulic gradients follow roughly those of the fluvial drainage systems at the surface (DAEE, 1974; Rebouças, 1976; Araujo et al, 1999; Rabelo and Wendland, 2009; Manzione et al, 2012; Cunha et al, 2007; Aguiar, 2012; Melo Junior, 2012). The directions of deep lateral flows are also likely to follow a similar pattern. In other words, there are indications of a close association between groundwater movements at shallow and deep levels with the fluvial drainage systems at the surface in many regions of Brazil.

Vieira and Hamza (2012) have presented evidences indicative of the occurrences of extensive lateral flows in the sedimentary basins of the Amazon region in the north, Parnaíba basin in the northeast and Paraná basin in the south. These three major regions of lateral flows are indicated in the map of Figure (3). In the case of Amazon region, the inferred direction of the lateral flow is from west to east, following roughly the same course as that of the Amazon River. In the case of Parnaiba basin, the inferred direction of flow is from south to north, following roughly a course almost parallel to that of the Parnaiba River. In the case of Paraná basin, the inferred direction of flow is from northeast to southwest in southern Brazil.

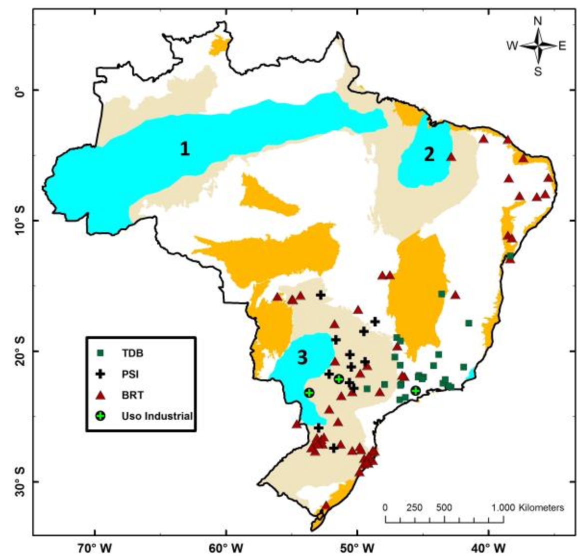

Figure (3) Regions of lateral flows of ground waters (shaded areas in blue color), in Paleozoic sedimentary basins of Brazil. 1- The Amazon region; 2- The Parnaiba basin; 3- Paraná basin. The symbols indicate localities of major thermal spring systems.

Interaction of Lateral Flow and Thermal Springs

The most conspicuous feature of figure (3) is the near total absence of thermal springs, in regions identified as having lateral flows (shaded areas in blue color). In fact, similar patterns are also present in many other sediment-covered regions of the world. Examples are sedimentary basins of Western Canada (Wright et al, 1994), Missouri-Mississippi valley in USA (Waring et al, 1965) and Gangetic plains in North-Central India (Roy and Gupta, 2012). In this context, it is important to examine processes responsible for mutual exclusion of thermal springs and areas of lateral flows of groundwater. Recently, Vieira and Hamza (2012) 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. Vieira et al (2013) have considered several possible modes of interaction between lateral flows of groundwater and up flows of thermal springs in a recent work. In the present work, we limit the discussion to Peclet-Rayleigh domains of thermal interactions.

Model Considerations: The interest in the present context is to explore the thermal characteristics of flow systems under the combined action of advection and thermal convection. To begin with, we note that Peclet number is a dimensionless quantity indicating the relative importance of energy transfer by advection to that by heat conduction. For this reason, the value of the Peclet number can be used in evaluation of the relative role of heat advection. However, pore-fluid movements can also take place by convection in hydrothermal systems in which the rate of transfer of heat energy is large enough. Generally, the critical Rayleigh number of a given hydrothermal system expresses the onset condition for convective pore-fluid flow. If the Rayleigh number, which is directly proportional to the temperature gradient, is equal to or greater than a critical value natural convection will take place in the porous medium.

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 eventual correlations between the dimensionless Peclet number and the critical Rayleigh number. The relation derived by Zhao et al (2008) serves as a convenient starting point. It is given as:

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

where the terms C_{11}, C_{22} and C_{21} are given by the relations:

$$C_{11} = -\left[\frac{1}{3} + \frac{2}{15} \cdot \left(K_1^*\right)^2\right] \qquad (2)$$

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

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

The quantity K_1^* is the dimensionless wave number (product of K_1, the wave number in the *x* direction, and *H*). Note that *C22* is a polynomial trial function.

Referring to equations (1 to 4) it is simple to note that, the critical Rayleigh number for the 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. This means that even very 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. This means considering the domain of down flows, where Peclet numbers are negative, as per the sign convention used by Zhao et al (2008). The extrapolation was carried out through the use of a polynomial that best fit the data of the benchmark problem 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 convective thermal gradients of the flow system.

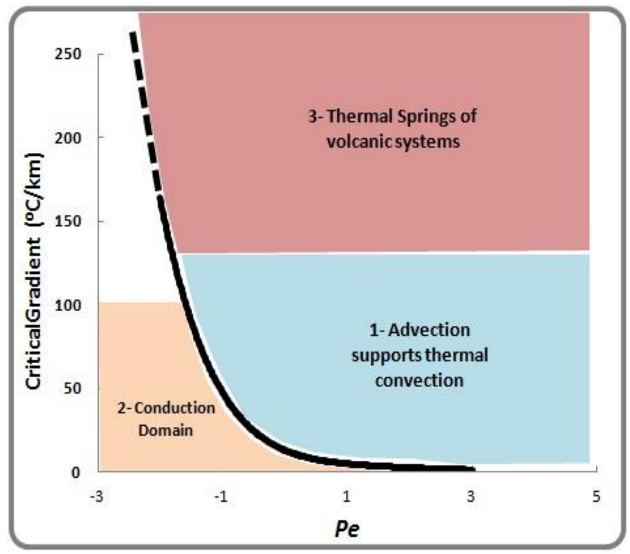

Figure (4) Relation between critical thermal gradients needed for convection and Peclet number.

The relation illustrated in Figure (4) may be considered as indicative of three distinct regions, designated here as domains 1, 2 and 3. In domain-1, where Peclet number is mostly positive, the advective forces act in the same direction as the thermal buoyancy force and as a result thermal fluids are transported upwards even when temperature gradients have relatively low values. In domain-2, where Peclet number is mostly negative, advection opposes thermal buoyancy forces of convection. In this case, upward movements of thermal waters are unlikely. In domain-3, where temperature gradients, and consequently thermal buoyancy forces, are quite large, up flow movements are almost independent of advective flows.

Results Obtained: Exploring the Peclet-Rayleigh relations is a convenient form of obtaining insights into the nature of interaction between lateral flows of groundwater and up flows of thermal springs in the Paleozoic basins of Amazon, Parnaiba and Paraná. Consider for example results for the Amazon basin, illustrated in figure (5). The thermal gradients of this region are in the range of 12 to 29 ^{o}C/km while the Peclet numbers are negative, falling in the range of -2 to 0. The domain of these values is located in the lower parts of the region to the left of the curve for critical gradients. This is actually domain – 1 of figure (4), implying that occurrences of thermal springs are unlikely.

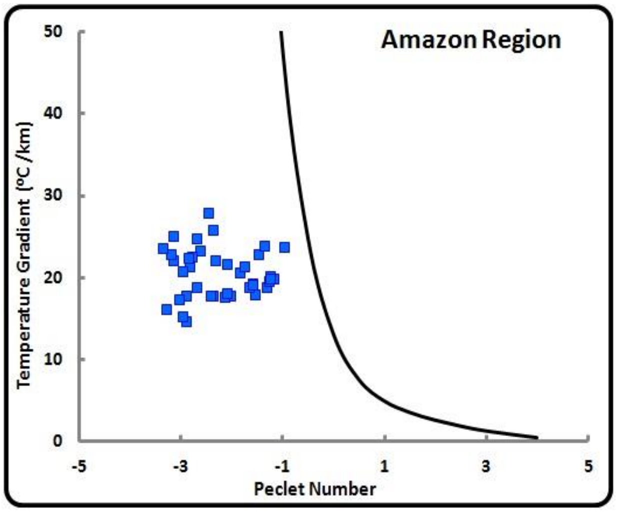

Figure (5) Relation between critical thermal gradients and Peclet number, for the Amazon region.

In the case of the Parnaiba basin, 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. As illustrated in figure (6), the observational data fall in domains on either side of the curve for critical gradients, indicating systems of down flow as well as up flow. This is unlike that of the Amazon region, where only down flow systems could be identified.

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. As in the case of Parnaiba basin the observational data fall in domains of on either side of the curve for critical gradients, indicating systems of down flow as well as up flow.

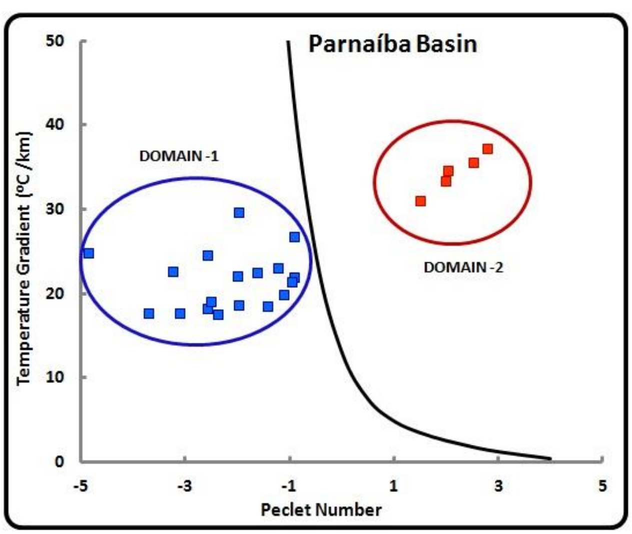

Figure (6) Relation between critical thermal gradients and Peclet number for the Parnaiba basin

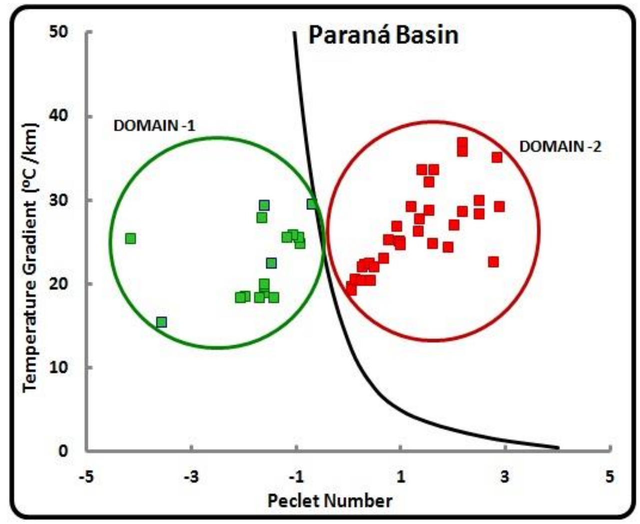

Figure (7) Relation between critical thermal gradients and Peclet number for the Paraná Basin.

Discussion and Conclusions

It is frequently argued that thermal springs occur only in areas with higher than average crustal heat flux. In fact, clusters of high-temperature springs are often associated with higher crustal heat flow. However, there are numerous cases where thermal springs are associated with crustal heat flux values much less than the global mean for continental regions. This is true of a number of springs in the southern and southeastern parts of Brazil. These are localities that have been deformed and cut by numerous large-scale normal and thrust faults that allow for the formation of short and deep groundwater flow systems. Though the availability of hydrogeological and geochemical data for the study area in Brazil is limited, there are indications that thermal springs do occur in some very low heat-flow settings.

Recently Ferguson and Grasby (2011) has presented arguments in favor of a significant correlation of spring temperature with flow system geometry and pointed out the relative importance of advection in groundwater flow systems. They also argue for a link between basin dimensions and discharge temperature, which implies that hydrogeology and structural geology are important in determining the distribution and characteristics of thermal springs. However, their arguments are based on circulation systems with depth-to-length ratios of 1:10. In cases of regional-scale lateral flows the depth to length ratios may be well in excess of 1:100.

Results obtained in the present work have pointed to general absence of thermal springs in areas of large-scale lateral flows of groundwater. This trend is found to be remarkably evident in the five basins (Acre, Solimões, Amazonas, Marajó and Barreirinhas) of the Amazon region, where thermal springs are absent in regions inferred to have lateral flows of groundwater. Similar conditions are also found to prevail in the central parts of the Parnaiba basin in the northeast and in the west-central parts of the Paraná basin in the south. We conclude that an understanding of the perturbing effects of lateral flow systems in the subsurface is important in assessment of geothermal resources.

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