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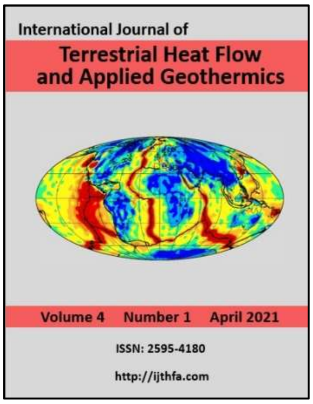

Method for estimating the depth of circulation of thermal and non-thermal waters in the upper crust

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Abstract

In this work we consider model formulations that allow better understandings of the relations between Darcy velocity and temperatures in coupled two-dimensional systems. The revised theoretical formulations are capable of accounting for the effects of heat transfer by fluid movements in horizontal and vertical directions. The models have been found useful in estimating the maximum and minimum depths of thermal and non-thermal waters in several geological units in Brazil. The best fitting values encountered are 1.8 to 2.7 km for the Paraná basin, 2.0 to 2.8 km for the Parnaiba basin, 1.6 to 2.3 km for the Amazon basins, 2.0 to 2.7 km for the San Francisco Province, 1.9 to 2.4 km for the Sergipe-Alagoas basins and 2.0 to 2.8 km for the Borborema Province. The models have also allowed estimation the average values of Péclet number and Darcy velocity for groundwater flows in these units. Note that higher horizontal velocities are associated with smaller depths of circulation. This is a natural consequence of the fact that in systems where horizontal velocities are high the quantities of vertical flows are less intense.

1. Introduction

The energy extraction schemes proposed for exploitation of hydrothermal resources depend on the values of model parameters such as the fluid temperature and specifications of resource recovery conditions. The main criteria used in exploration of resources are depth and temperature.

Among the many possible techniques available for estimation of in-situ resource temperature those based on the chemical and isotopic characteristics have wide acceptance. This technique, widely known as the “geochemical method”, makes use of the so-called chemical geothermometers of silica (quartz and chalcedony), and those that make use of the dissolved contents of sodium, potassium and calcium (Truesdell, 1976; Fournier and Potter, 1982). A major difficulty in employing this procedure is the uncertainty in the determination of the depth of circulation thermal waters.

This approach is possible since the temperature and pressure of hydrothermal flow are functions of spatial coordinates and depends on the thermal energy exchange in the reservoir and heat loss during upflow. A schematic diagram of a typical hydrothermal system is to develop illustrated in Figure 1. The purpose of this work is to develop improvements in models employed for describing thermal heat exchange processes operating within the component systems that constitute a hydrothermal system.

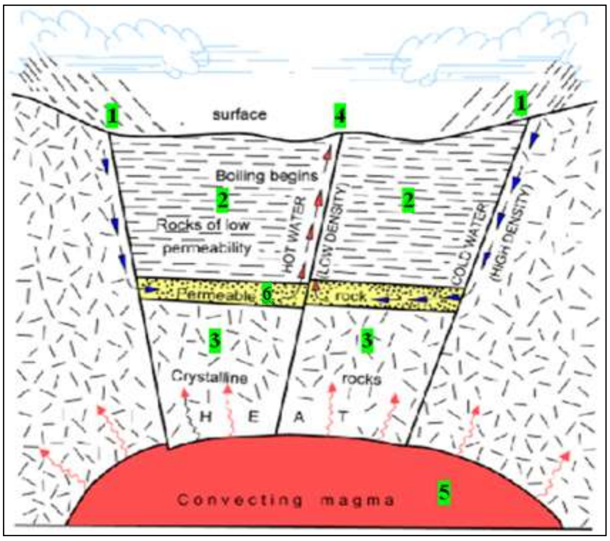

Figure 1 - Schematic diagram of the main components of a typical hydrothermal system. (1) Recharge area; (2) Low permeability of cover rocks; (3) Confining rock formations; (4) discharge area; (5) source rock of thermal energy; (6) host rocks for the reservoir (Adapted with modifications from White, 1973).

2. Model Considerations

The physical models dealing with the problem of fluid flows are based on the solution of fundamental equations that govern fluid movements. However, in the case of coupled heat and mass transport looking for solutions following Navier-Stokes equations becomes difficult, since the microscopic details of the flow geometry are unknown. To overcome such problems a possible solution is to make use of the fact that thermal energy flows continuously between subsurface strata and groundwater and this implies action of a natural tracer in underground fluid flows. About a century back geophysicists considered the possibility that thermal energy is transferred along the flow path between geological media and subsurface fluids in the pore space (Constantz et al., 2008).

The use of heat as a tracer in measurements of temperature gradients is useful since temperature is a robust parameter for tracing. Temperature values are available in direct or indirect measurements, as for example geochemical data. Figure 2 is a schematic illustration of a typical hydrothermal system. A model based on this figure may be used in a revised formulation of mathematical problem of simultaneous flow of fluid and heat. Two-dimensional cartesian coordinates for porous media have been employed in studies of terrestrial crust (adapted from Stallman, 1965).

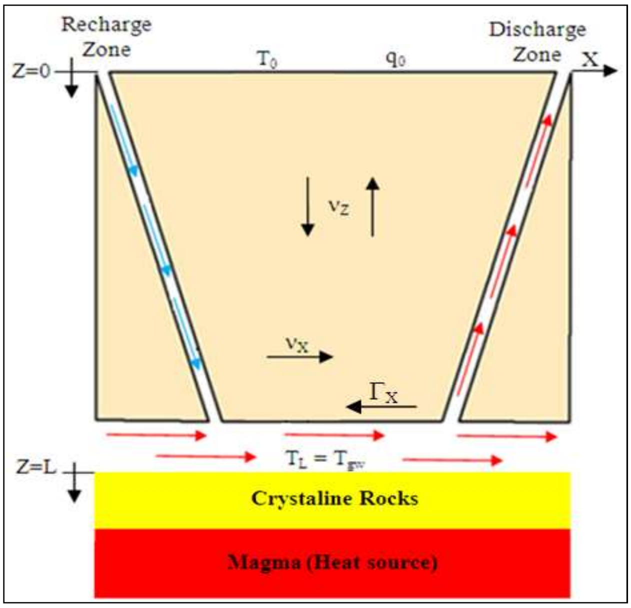

Figure 2 - Conceptual model of a typical hydrothermal system (Adapted from Vieira et al., 2013).

The formulation of this problem is in general based on the following equation:

$$\left\{\left[\frac{\partial}{\partial Z}\left(\lambda_Z(T)\frac{\partial T}{\partial Z}\right)\right]+\left[\frac{\partial}{\partial X}\left(\lambda_X(T)\frac{\partial T}{\partial X}\right)\right]\right\} \tag{1}$$

$$-c_W\rho_W\left[\nu_Z\frac{\partial T}{\partial Z}+\nu_X\frac{\partial T}{\partial X}\right]+f(X,Z)=c\rho\frac{\partial T}{\partial t}$$

where the terms used in the above equation and Figure 2 may be described as follows: T(X, Y, t) is temperature at the spatial coordinates X, Z at time t, T_0 the temperature at the surface (Z=0), T_L Temperature at depth (Z=L), L the depth of the reservoir, λ_X and λ_Z the components of thermal conductivity of the fluid saturated rock matrix along the coordinate directions, ν_X and ν_Z are components of fluid velocities along the coordinate directions. In addition, the fluid parameters are assumed to be constants. It includes the specific heat (c_W), the density (ρ_W), the volumetric heat capacity (C_W), the density of rock-fluid matrix (ρ), the specific heat (c), a function $f(X, Z)$ that describes heat sources and Γ_X the temperature gradient in the X direction. With the exception of wells located in recharge and discharge zones flow of fluids occur in the horizontal and vertical directions.

Equation 1 may be simplified for a system in which thermal conductivity is independent of temperature, the medium is homogeneous and isotropic, thermal regime is in steady state and where heat sources are absent. For such systems the equation may be rewritten as:

$$\frac{\partial^2 T}{\partial Z^2}+\frac{\partial^2 T}{\partial X^2}-\frac{c_W\rho_W}{\lambda}\left[\nu_Z\frac{\partial T}{\partial Z}+\nu_X\frac{\partial T}{\partial X}\right]=0 \tag{2a}$$

Equation 2a may be simplified if it is assumed that diffusion of heat in the vertical direction is dominant than that in the horizontal direction. This condition may be formulated as:

$$\frac{\partial^2 T}{\partial Z^2} >> \frac{\partial^2 T}{\partial X^2} \tag{2b}$$

For systems in which the horizontal variation of temperature is negligible compared to the vertical gradient equation 2a may be simplified as:

$$\frac{d^2T}{dZ^2}-\frac{c_W\rho_W\nu_Z}{\lambda}\frac{dT}{dZ}-\frac{c_W\rho_W\nu_X}{\lambda}\Gamma_X=0 \tag{3a}$$

The appropriate boundary conditions are:

$$T(Z=0)=T_0 \quad \text{(the surface temperature)} \tag{3b}$$

$$T(Z=L)=T_L \quad \text{(the bottom boundary temperature)} \tag{3c}$$

For the system described by Equation 3 we may consider three distinct situations that allow estimation of the depth of the hydrothermal system:

a) Model A ($\nu_Z = 0$; $\nu_X = 0$ and $\Gamma_X = 0$);

b) Model B ($\nu_Z \neq 0$; $\nu_x = 0$ and $\Gamma_X = 0$);

c) Model C ($\nu_Z \neq 0$; $\nu_X \neq 0$ and $\Gamma_X \neq 0$);

We consider now solutions for these models.

2.1. Model A ($\nu_Z = 0$; $\nu_X = 0$ and $\Gamma_X = 0$).

In this model which assumes that $\nu_Z = 0$, $\nu_X = 0$ and $\Gamma_X = 0$, Equation 3 may be rewritten as:

$$\frac{d^2T}{dZ^2}=0 \tag{4}$$

The boundary conditions for the system described by equations 3a and 3b allows us to derive the solution of 4 as:

$$T(Z)=\left(\frac{T_L-T_0}{L}\right)Z+T_0 \tag{5}$$

The anti-derivative of 4 when multiplied by the thermal conductivity (λ) leads to the solution for heat flux (q) as:

$$q_0 = \lambda\left(\frac{T_L - T_0}{L}\right) \tag{6}$$

This is the linear relation proposed by Swanberg and Morgan (1978; 1980) for estimating heat flux using silica content of thermal waters in western USA. The relation for heat flux may be written as:

$$T_{SiO_2} = mq_0 + b \tag{7}$$

where T_{SiO2} is the reservoir temperature derived from the silica content of thermal waters, *m* is a constant related to the depth of circulation of thermal waters and *b* is the mean annual surface temperature, referred to in Equation 6. Alexandrino and Hamza (2018) used this method for calculating values of *m* and *b* for eastern Brazil and obtained values respectively of 1071±125 $^{\circ}Cm^2W^{-1}$ and 25.5±6.7°C. The relation is illustrated in Figure 3.

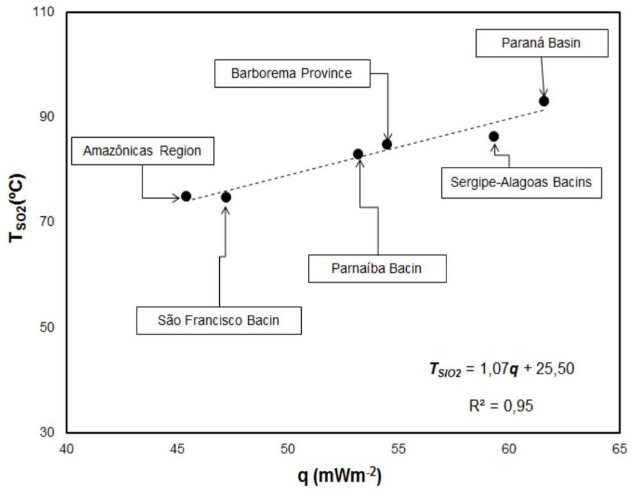

Figure 3 - Relation between silica temperatures and heat flow values for the main geological provinces in Brazil (Source: Alexandrino and Hamza 2018).

The relation for heat flux derived from Equation 7 may also be written as:

$$q_0 = \frac{T_{SiO_2} - T_0}{m} \tag{8}$$

Equating the relations 6 and 8 and knowing that T_L may be considered as equivalent to T_{SiO2} the relation for depth of circulation may be written as:

$$L = m\lambda \tag{9}$$

2.2. Model B ($\nu_Z \neq 0$; $\nu_X = 0$ and $\Gamma_X = 0$).

In this model it is assumed that $\nu_Z \neq 0$, $\nu_X = 0$ and $\Gamma_X = 0$, which allows rewriting Equation 3a as:

$$\frac{d^2T}{dZ^2} - \frac{c_W \rho_W v_Z}{\lambda}\frac{dT}{dZ} = 0 \tag{10}$$

The boundary conditions are given in equations 3a and 3b and the solution may be written as:

$$T(Z) = (T_L - T_0)\left[\frac{1 - e^{\frac{(v_Z.c_W.\rho_W.L)}{\lambda}\frac{Z}{L}}}{1 - e^{\frac{(v_Z.c_W.\rho_W.L)}{\lambda}}}\right] + T_0 \tag{11}$$

This is the solution described in the work of Bredehoeft and Papadopulos (1965). The solution may be simplified using the ratio of convective and conductive components of heat flow, the Péclet number (Pe):

$$Pe = \frac{v_Z.c_W.\rho_W.L}{\lambda} \tag{12}$$

For Pe > 1 conductive heat flux is dominant while convective heat flux is dominant for Pe < 1. Using Equation 12 in 11 we get the relation:

$$T(z) = T_0 + \frac{1 - e^{Pe\frac{z}{L}}}{1 - e^{Pe}}(T_L - T_0) \tag{13}$$

The above equation may be written as

$$\frac{T(z) - T_0}{T_L - T} = \frac{1 - e^{Pe\frac{z}{L}}}{1 - e^{Pe}} \tag{14}$$

Equation 14 may also be used for estimating the depth of circulation provided we make the assumption that at the depth value of Z of 0,99 the ratio of temperatures on the left-hand side of 14 is given by the relation:

$$\frac{T(z) - T_0}{T_L - T} = 0{,}99$$

The error in introducing the above relation is relatively minor when compared with the uncertainties in the remaining parameters. On the other hand, this condition allows us the solution as:

$$0{,}99\left(1 - e^{Pe}\right) - \left(1 - e^{0{,}99\,Pe}\right) = 0 \tag{15}$$

We need one more equation in completing this model. For this purpose, Equation 13 is differentiated with respect to the depth *Z* and multiplied by thermal conductivityλ, which is the relation for heat flux in Equation 8:

$$\left(\frac{Pe\lambda}{L}\right)\frac{(T_L - T_0)}{(1 - e^{-Pe})}e^{Pe\frac{z}{L}} = \frac{T_{SiO_2} - T_0}{m} \tag{16}$$

Since $T_L = T_{SiO2}$ at $Z = L$ Equation 16 may be written as:

$$v_z c_W \rho_W\, e^{Pe} - \left[\frac{q_0}{T_L - T_0}\right]\left(1 - e^{Pe}\right) = 0 \tag{17}$$

The equations 12, 15 and 17 form a non-linear system the solution of which allows us to estimate vertical velocity ν_Z, depth of the reservoir, L and the Péclet number, Pe.

This system may be solved using appropriate numerical methods:

$$\begin{cases} Pe\lambda - v_Z.c_W.\rho_W.L = 0 \\ 0{,}99\left(1 - e^{Pe}\right) - \left(1 - e^{0{,}99Pe}\right) = 0 \\ v_z c_W \rho_W\, e^{Pe} - \left[\dfrac{q_0}{T_L - T_0}\right]\left(1 - e^{Pe}\right) = 0 \end{cases} \tag{18}$$

In cases where the value of Darcy velocity is known 18 may be written as:

$$\begin{cases} Pe\lambda - v_Z . c_W . \rho_W . L = 0 \\ v_z c_W \rho_W \, e^{Pe} - \left[\dfrac{q_0}{T_L - T_0} \right] \left(1 - e^{Pe}\right) = 0 \end{cases} \tag{19}$$

2.3. Model C (νz ≠ 0; νx ≠ 0 and Γx ≠ 0).

In this model $\nu_Z \neq 0$, $\nu_X \neq 0$ e $\Gamma_X \neq 0$, which imply a complete solution to Equation 3a:

$$\frac{d^2T}{dZ^2} - \frac{c_W \rho_W \nu_Z}{\lambda} \frac{dT}{dZ} - \frac{c_W \rho_W \nu_X}{\lambda} \Gamma_X = 0 \tag{20}$$

The boundary conditions are given by equations 3a and 3b and using the relation for Péclet number by Equation 12 the solution for 20 may be written as:

$$T(z) = T_0 + (T_L - T_0) \left[\left(\frac{1 - e^{Pe\frac{z}{L}}}{1 - e^{Pe}} \right) + \frac{\nu_X \Gamma_X L}{\nu_Z} \left(\frac{1 - e^{Pe\frac{z}{L}}}{1 - e^{Pe}} - \frac{Z}{L} \right) \right] \tag{21}$$

This solution is similar to that obtained by Clauser and Villinger (1990), Lu and Ge (1996), Reiter (2001) and Verdoya et al. (2008).

Note that Equation 21 reduces to 13 for the case $\nu_X = 0$ or $\Gamma_X = 0$. In evaluating 21 we also introduce as before the limiting condition that at the depth values of Z of 0,99L the temperature is:

$$\frac{T(z) - T_0}{T_L - T} = 0{,}99$$

Which allows rewriting 21 as:

$$\left[\left(\frac{1 - e^{0{,}99Pe}}{1 - e^{Pe}} \right) + \frac{\nu_X \Gamma_X L}{\nu_Z} \left(\left(\frac{1 - e^{0{,}99Pe}}{1 - e^{Pe}} \right) - 0{,}99 \right) \right] - 0{,}99 = 0 \tag{22}$$

We need another equation for the solution, and this may be obtained as before by differentiating 21 with respect to Z and multiply by λ, thereby reaching the solution:

$$\left(\frac{Pe\lambda}{L} \right) \left[\left(\frac{e^{Pe\frac{z}{L}}}{1 - e^{Pe}} \right) + \frac{\nu_X \Gamma_X L}{\nu_Z} \left(\left(\frac{e^{Pe\frac{z}{L}}}{1 - e^{Pe}} \right) - \frac{1}{Pe} \right) \right] - \frac{1}{m} = 0 \tag{23}$$

Evaluating (24) at Z = L we get:

$$v_z c_W \rho_W \left\{ \left[\frac{e^{Pe}}{\left(1 - e^{Pe}\right)} \right] + \left[\frac{\nu_X \Gamma_X L}{\nu_Z} \left(\left(\frac{e^{Pe}}{\left(1 - e^{Pe}\right)} \right) - \frac{1}{Pe} \right) \right] \right\} - \left[\frac{q_0}{T_L - T_0} \right] = 0 \tag{24}$$

Equations 12, 21 and 24 form a non-linear system that allow estimation of ν_Z, L and Pe. As before use may be made of appropriate numerical methods for evaluating velocity ν_X and heat flux Γ_X.

$$\begin{cases} Pe\lambda - \nu_Z . c_W . \rho_W . L = 0 \\ \left[\left(\dfrac{1 - e^{0{,}99Pe}}{1 - e^{Pe}} \right) + \dfrac{\nu_X \Gamma_X L}{\nu_Z} \left(\left(\dfrac{1 - e^{0{,}99Pe}}{1 - e^{Pe}} \right) - 0{,}99 \right) \right] - 0{,}99 = 0 \\ \nu_Z c_W \rho_W \left\{ \left[\dfrac{e^{Pe}}{\left(1 - e^{Pe}\right)} \right] + \left[\dfrac{\nu_X \Gamma_X L}{\nu_Z} \left(\left(\dfrac{e^{Pe}}{\left(1 - e^{Pe}\right)} \right) - \dfrac{1}{Pe} \right) \right] \right\} - \left[\dfrac{q_0}{T_L - T_0} \right] = 0 \end{cases} \tag{25}$$

This case also allows for derivation of the relations for cases where Darcy velocity is known. The systems of equations 25 reduce to two equations:

$$\begin{cases} Pe\lambda - \nu_Z c_W . \rho_W . L = 0 \\ \nu_z c_W \rho_W \left\{ \left[\dfrac{e^{Pe}}{\left(1 - e^{Pe}\right)} \right] + \left[\dfrac{\nu_X \Gamma_X L}{\nu_Z} \left(\dfrac{e^{Pe}}{\left(1 - e^{Pe}\right)} + \dfrac{1}{Pe} \right) \right] \right\} - \left[\dfrac{q_0}{T_L - T_0} \right] = 0 \end{cases} \tag{26}$$

3. Tests using observational data

To estimate the depth of circulation in the proposed models we need to know the value of thermal conductivity λ, heat flow q_0, surface temperature T_0, temperature T_L, specific heat of the fluid c_W and the density of the fluid ρ_W.

Table 1 provides a list of thermal conductivity values estimated by Vieira (2015). The values of heat flow q_0 and reservoir temperature T_{SiO2}, in Table 1, were estimated by Alexandrino and Hamza (2018), using the geochemical method (silica concentration) for the main Brazilian tectonic provinces, as shown in Figure 4.

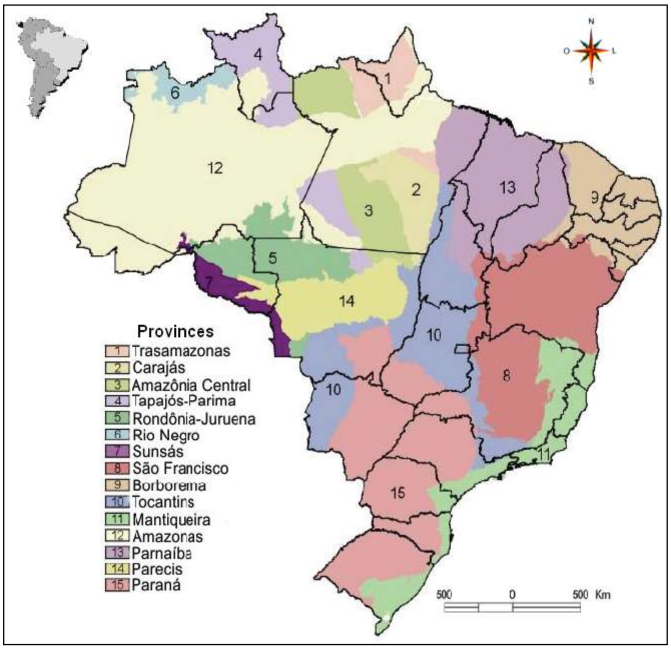

Figure 4 - The Brazilian Structural Provinces (Adapted from CPRM, 2003).

The value of surface temperature (T_0) used was estimated by Alexandrino and Hamza (2018) based on Figure 3 and its value is 25.5±6.7 ºC. The values assumed for specific heat of the fluid (c_W) has been 4.18 kJ/ºC and the density of the fluid (ρ_W) 1000 kg/m^3.

Table 1 - Physical parameters used to estimate the circulation depth.

Region	N	λ (W/m/ºC)	q_0 (mW/m^2)	T_{SiO2} (ºC)
Parana basin	540	2.5 ± 0.4	63 ± 17	93 ± 18
Parnaiba Basin	56	2.6 ± 0.5	54 ± 15	83 ± 19
Amazon Region	39	2.1 ± 0.3	46 ± 13	75 ± 18
São Francisco Basin	722	2.6 ± 0.4	47 ± 13	75 ± 18
Sergipe Alagoas basins	38	2.2 ± 0.3	58 ± 15	86 ± 24
Borborema Province	615	2.6 ± 0.8	56 ± 25	85 ± 18

4. Results and discussion

The results presented in this section are divided according to the three models described in this work.

The Table 2 presents the depth values of the thermal and non-thermal water circulation for each of the provinces analyzed in this work for model A, in this model, the heat transfer mode is purely conductive. This implies that the Péclet number is equal to zero and also the movement of fluids in the vertical as well as horizontal directions is not evaluated.

Table 2 - Estimated circulation depths for Model A.

Region	Model A
	L (km)
Parnaiba basin	2.8 ± 0.4
São Francisco	2.8± 0.5
Borborema	2.8 ± 0.6
Paraná basin	2.7 ± 0.5
Sergipe-Alagoas	2.4 ± 0.4
Amazon basins	2.2 ± 0.6

Table 3 shows the results obtained from model B. Therefore, the estimates for thermal and non-thermal water circulation depth, Peclet number and Darcy velocity are presented.

In model B the predominant mode of heat transfer is conduction, we can make this affirmation because of small values of Peclet number and Darcy velocity, estimated by this model. Therefore, the values of the circulation depth are similar to those estimated by model A, this fact allows us to state that models A and B estimate the maximum depth of circulation, the basic difference between them, occurs only in relation to the estimated parameters, because while model A provides only the depth of circulation, model B not only estimates the depth of circulation, but also allows us to estimate the number of Peclet and the Darcy velocity.

Relatively high values of circulation depths were found Paleozoic intracratonic basins.

Table 3 - Circulation depths estimated from Model B.

Region	Model B		
	L (km)	Pe	ν_Z (m/s)
Parnaiba basin	2.8 ± 0.4	2.0E-05 ± 9.7E-06	4.5E-15 ± 2.8E-15
Borborema	2.8 ± 0.4	1.2E-05 ± 1.5E-06	2.8E-15 ± 1.2E-15
Paraná basin	2.7 ± 0.3	2.0E-05 ± 4.3E-06	4,4E-15 ± 1.6E-15
São Francisco	2.7 ± 0.4	1.5E-05 ± 1.2E-06	3.4E-15 ± 1.4E-15
Sergipe-Alagoas	2.3 ± 0.3	1.6E-05 ± 4.3E-06	3.8E-15 ± 1.3E-15
Amazon basins	2.3 ± 0.3	5.3E-05 ± 8.7E-06	1.2E-14 ± 2.4E-15

Table 4 presents the results obtained from the C model. The main characteristic of this model is to consider the influence of heat and fluid transport in the horizontal direction. The product of the geothermal gradient Γ_X by the Darcy velocity ν_X represents this influence.

These magnitudes operate in the same direction, but their meanings are opposite, for this reason the product $\Gamma_X\ \nu_X$ is always negative and as the typical magnitude of Γ_X is 10^{-2} and that of X varies between 10^{-4} to 10^{-10} (Domenico and Schwartz, 1990; Jobmann and Clauser, 1994; Pasquale et. al., 2010; Omer, 2017) we considered the influence for four different values for the product $\Gamma_X\ \nu_X$. Note that higher horizontal velocities are associated with shallower depths of circulation. This is a natural consequence of the fact that the quantities of down going fluids are less for higher horizontal velocities.

Table 4 - Circulation depths estimated from Model C.

Region	Model C			
	$\nu_X\,\Gamma_X$ (ºC/s)	L (km)	Pe	ν_Z (m/s)
Paraná basin	-1.0E-06	1.8	2.3E-03	7.4E-13
	-1.0E-08	2.6	2.9E-04	6.7E-14
	-1.0E-10	2.6	6.2E-05	1.4E-14
	-1.0E-12	2.7	2.6E-05	5.9E-15
Parnaiba basin	-1.0E-06	2.0	2.6E-03	8.3E-13
	-1.0E-08	2.7	3.0E-04	6.9E-14
	-1.0E-10	2.8	6.3E-05	1.4E-14
	-1.0E-12	2.8	1.3E-05	3.0E-15
Amazon basins	-1.0E-06	1.6	2.5E-03	7.7E-13
	-1.0E-08	2.2	2.3E-04	5.2E-14
	-1.0E-10	2.2	6.5E-05	1.5E-15
	-1.0E-12	2.3	1.4E-05	3.0E-15
São Francisco	-1.0E-06	2.0	2.8E-03	8.6E-13
	-1.0E-08	2.6	3.3E-04	7.8E-14
	-1.0E-10	2.7	5.9E-05	1.3E-14
	-1.0E-12	2.7	2.5E-05	5.8E-15
Sergipe-Alagoas	-1.0E-06	1.9	4.5E-03	1.2E-12
	-1.0E-08	2.3	2.7E-04	6.1E-14
	-1.0E-10	2.3	9.4E-05	2.1E-14
	-1.0E-12	2.4	5.4E-05	1.2E-15
Borborema	-1.0E-06	2.0	2.6E-03	8.3E-13
	-1.0E-08	2.7	3.0E-04	7.0E-14
	-1.0E-10	2.8	5.5E-05	1.2E-14
	-1.0E-12	2.8	1.6E-05	3.6E-15

In Table 4 we can verify that for minimum values of Γ_X ν_X also have minimum values of Péclet number and Darcy velocity in vertical direction. This implies that these values are directly proportional.

In this model the predominant heat transfer mode is conduction, but the convective heat transfer mode increases its influence on the process of hydrothermal circulation, when the values Γ_X ν_X increase.

The increase in factor Γ_X ν_X causes a decrease in the depth of circulation and the estimated values for Péclet number and Darcy velocity. Consequently, the depth of circulation is inversely proportional to the value Γ_X ν_X. This occurs because in this condition there is greater amount of heat transport and a smaller quantity of fluids available for percolation in the vertical direction vertical in the circulation system.

5. Conclusions

The results obtained by models A and B are similar. This is because both models do not consider the influence of the horizontal variation of heat between the recharging zone and the discharge zone existing in a hydrothermal circulation system. Therefore, these models capture only the maximum depth of circulation.

The model C because it considers the horizontal variation of heat allows estimating the depth of circulation more accurately. As shown in Table 4 when factor $\Gamma_X\nu_X \rightarrow 10^{-12}$, the value of the circulation depth estimated by this model approximates the values estimated by models A and B.

However, when the value of plot $\Gamma_X\nu_X \rightarrow 10^{-6}$, the circulation depth is lower compared to those estimated by models A and B. Therefore, using this model, it is possible to establish the maximum and minimum depths of hydrothermal circulation. Another interesting result is that regions with higher values of horizontal velocities are associated with lower depths of vertical circulation.

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