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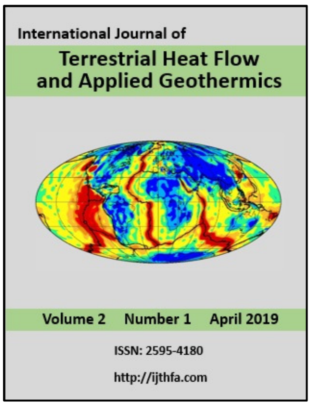
Paleo heat flow in areas of Sedimentary Exhalative (SEDEX) deposits of Eastern Brazil

Sundaram Iyer [1] and Valiya Hamza [2]

[1] (Retired) Department of Physics and Astronomy, University of Calgary, Alberta, Canada.
[2] Department of Geophysics, National Observatory, Rio de Janeiro, Brazil.

Email address

ammulu.iyer@gmail.com (S. Iyer)
Corresponding author



Keywords

Paleo Heat Flow,
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Abstract

Representative values of fluid inclusion temperatures and radiogenic heat production values have been compiled as part of an attempt to determine paleo heat flow in areas sedimentary exhalative (SEDEX) deposits in thirteen localities of eastern Brazil. The results obtained indicate heat flow in excess of 80 mW/m^2 in areas of mineral bearing sulphide ore deposits, during periods of ore forming processes. Such anomalously high heat flow are more than twice the present-day values for stable tectonic units of Precambrian age. There are indications that high heat flow values were sustained by circulation of hydrothermal fluids in the upper crust, during periods not exceeding a few hundred million years. The resulting geothermal episodes may be considered as constituting short-period “heat pulses” occurring in stable tectonic environments, generated by magma emplacements in the upper crust, leading to formation of areas of sulfide ore deposits. Model simulations indicate that subsidence episodes induced by stretching and magma under-plating constitute the mechanisms for high heat flow during the ore-forming processes.

1. Introduction

Considerable progress has been achieved over the last few decades in outlining present state of terrestrial heat flow variations in both continental and oceanic regions. Nevertheless, very few efforts have been made in estimating heat flow variations of the geologic past, of major geologic units of the Earth. Empirical relations between tectonic age and present heat flow patterns provide initial frameworks for estimating past thermal conditions of the lithosphere. However, problems in acquiring reliable paleothermal data and difficulties in developing suitable methods of data analysis and interpretation techniques have impeded better understanding of paleo heat flow variations of the geologic past. Nevertheless, recent progress obtained in mineral thermometry and temperatures of fluid inclusions have opened up new perspectives (Iyer, 2001). In the present work we consider use of temperatures of fluid inclusions in determining paleothermal conditions in areas of sedimentary exhalative (SEDEX) deposits. It is well known that massive sulphide deposits of volcanic origin (VMS) are major sources of metals such as Zinc, Copper, Lead, Gold and Silver. There are more than 1000 such deposits worldwide. Thus, the possibility of outlining paleo heat flow trends on global scale appears promising.

The objective of this work is to use both descriptive information and conceptual models for determination of paleo heat flow in locations of SEDEX deposits. The mineral system schemes put forward by various authors share critical elements of hydrothermal ore-forming processes such as sources of fluids, ore-transporting ligands, metals, drivers of fluid movement and outflow zones for discharge of spent hydrothermal fluids. They typically occur at or near the seafloor in submarine volcanic environments and are classified according to base metal content or host-rock lithology. Such deposits form through focused discharge of hot, metal-rich hydrothermal fluids.

A common feature of SEDEX deposits is that they are formed in extensional tectonic settings, including both oceanic sea-floor spreading and arc environments. Most significant onshore mining districts are defined by deposits formed within rifts or calderas. Their clustering is further attributed to a common heat source that triggers large-scale subseafloor fluid convection systems. These subvolcanic intrusions may also supply metals to the hydrothermal systems through magmatic devolatilization. SEDEX camps can be further characterized by the presence of thin, but areally extensive, units of ferruginous chemical sediment formed from exhalation of fluids and distribution of hydrothermal particulates.

Available information on fluid inclusions, mineral assemblages, and isotopic data indicate the deposits formed at 100° to 200° C from fluids with neutral to moderately acidic pH and salinities that range from 10 to 30 percent TDS. Chemical modeling of metal solubility indicates that 100°C as the lower limit for temperatures needed for moving ore-forming quantities of Pb and Zn (Cooke et al, 2000; Emsbo, 2000). On the basis of this constraint, Southgate et al (2006) have proposed the concept of a "thermal leaching window" as a temperature interval of burial (≈150–250°C at normal geothermal gradients) through which a stratigraphic package of metal source rock can be efficiently leached, liberating metals to a deep basin brine. In the present work, representative values of fluid inclusion temperatures and radiogenic heat production values have been compiled as part of an attempt to determine paleo heat flow in areas sedimentary exhalative (SEDEX) deposits in thirteen localities of eastern Brazil (Figure 1).

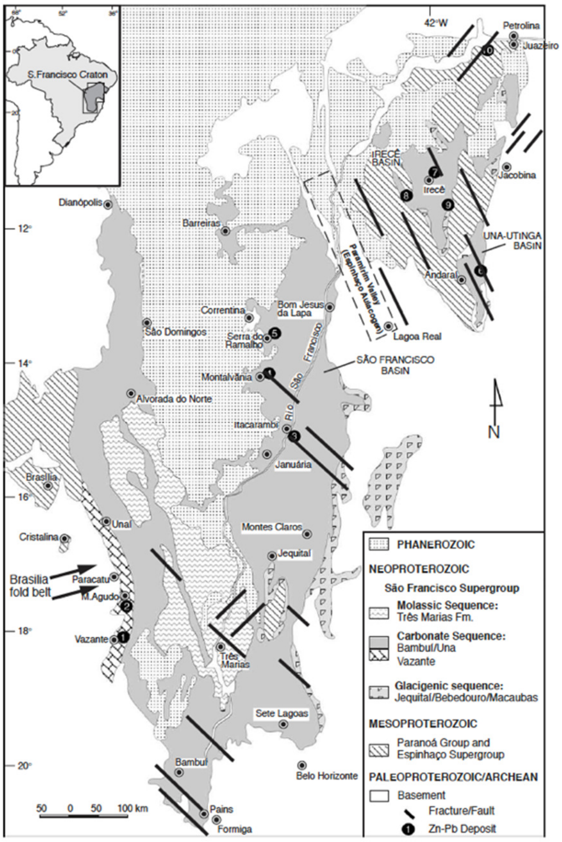

Figure 1 - Locations of SEDEX deposits in eastern Brazil Modified after Misi et al, 2005).

2. Radiogenic Heat Production and Heat Flow

Examination of the available geothermal data set reveal systematic changes in regional heat flow in the Brazilian platform. For example, Archean Cratonic areas are found to have heat flow in the range of 30 to 40 mW/m^2 while the corresponding range for fold belts of late Proterozoic age is 40 to 60 mW/m^2. Such regional scale variations have often been interpreted as arising from the dependence of heat flow on the tectonic age. In the present context, the interest is in understanding heat flow variations in areas of Precambrian sedimentary sequences. A direct approach to this problem is difficult in view of the scarcity and the highly non-uniform geographic distribution of available data. Nevertheless, an overall pattern can be put together making use of regionally representative values of heat flow and radiogenic heat production. A summary of the relevant data, presented in table 1, has been found useful for setting bounds in model studies.

Table 1 - Representative values of present heat flow (Q) and radiogenic heat production (A) in areas of sulfide ore deposits. The heat flow data are from Hamza and Munoz, 1996. Heat production values were calculated using data reported by Ferreira et al, 1979; Iyer et al, 1984; Roque, 1995; Sighinolfi and Sakai, 1977; Vitorello et al, 1980.The fluid inclusion temperature data are from: 1- D'el-Rey Silva et al, 1998; 2-Lindenmayer, 1998; 3-Fleischer and Espourteille, 1998; 4-Misi et al, 1998; 5-Oliveira, 1998; 6-Remus et al, 1998; 7-Daitx, 1998; 8-Araujo, 1998.

Ore deposit	Age (b.y.)	Q (10^{-3} W/m^2)	A (10^{-6} W/m^3)	Fluid Inclusion Temperature (^0C)
Caraíba	1.9 – 2.25	37	1.1	300[1]
Salobo	1.88 – 2.86	(51)	(1.6)	370[2]
Boquira	2.00 – 2.60	(51)	(1.6)	350[3]
Nova Redenção	0.65	(51)	(1.6)	162[4]
Morro Agudo	0.65	52	1.0	250[5]
Vazante	0.65	46	1.4	260 – 294[5]
Camaquá, S. Maria	0.56 – 0.59	77	(2.7)	210 – 300[6]
Perau, Canoas	1.10 – 1.20	(66)	(2.7)	350[7]
Palmeiróp olis	1.17 – 1.27	(63)	(2.8)	300[8]

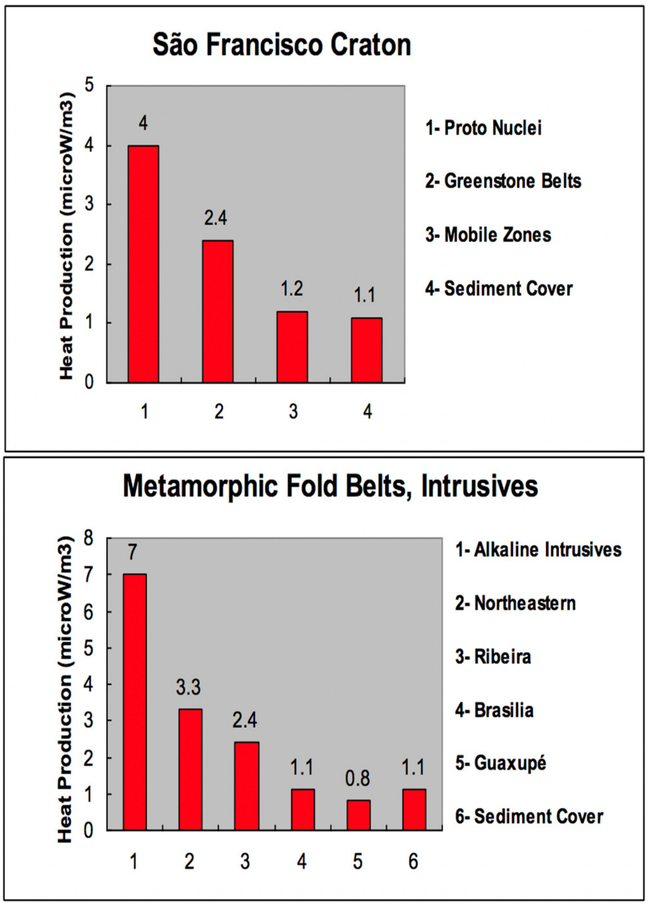

Figure 2. Histograms of radiogenic heat production values in the Cratonic areas (upper panel) and metamorphic fold belts (lower panel) of eastern Brazil.

Histograms of radiogenic heat production values in the cratonic areas and metamorphic fold belts of eastern Brazil are presented in Figure 2. Referring to the upper panel of this figure note that high heat production values are encountered in areas of proto nuclei, while sediment cover over cratonic units and mobile zones have low heat production. The greenstone belts seem to be characterized by intermediate values. Referring to the lower panel of this figure note that high heat production values are encountered in areas of alkaline intrusive while areas of sediment cover and mobile belts have lower values.

3. Mobility of U in SEDEX Deposits

Under oxidizing conditions U, the main radiogenic heat generating element, becomes hexavalent uranyl ions (UO_{2+}) that forms water soluble compounds and becomes mobile. The loss of the radioactive element yields lower radiogenic heat production data. To overcome this problem Iyer et. al (1999) have suggested the use of lead isotope data to calculate the present as well as paleo U and Th concentrations. This study demonstrates the usefulness of Pb isotopes to determine quantitatively the mobility of U and Th in different geological environments. The method is based on the comparison of the calculated present-day U and Th concentrations required to yield the Pb isotope composition in the samples with the actual present-day concentrations of U and Th obtained by direct measurement.

The geological formations studied include the Neoproterozoic carbonate sediments of the Bambui Group, Archean/Paleoproterozoic granite-greenstone terrain of the Contendas-Mirante Complex and a Proterozoic ortho-gneisses hosting U deposit in Lagoa Real. All these formations are in the São Francisco Craton, Brazil. The results indicate that large scale mobility of U occurred in the studied carbonate sedimentary rocks and deformed ortho-gneisses. In comparison, the undeformed calc-alkaline volcanics and granitic rocks retained much of their U and Th. The study also indicates a larger U mobility in near surface and oxidizing conditions.

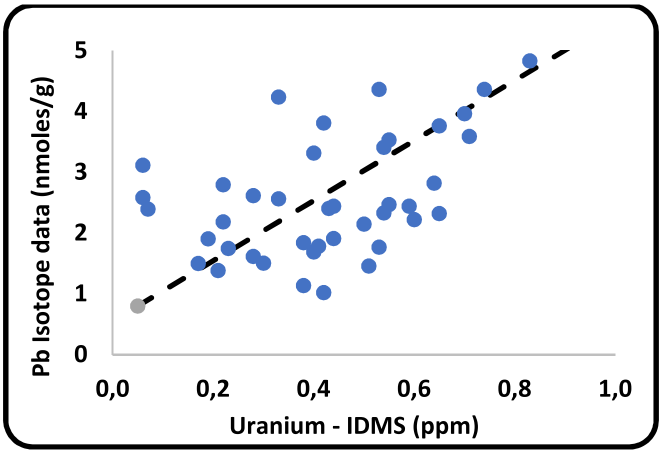

Figure 3 - Uranium loss in samples from the MF 7 outcrop in the sedimentary rocks of Bambuí group, Brazil.

The mobility of the radiogenic heat producing elements poses a major hurdle in the modelling of the crustal temperature and paleo thermal regime. This hurdle can be surmounted by using Pb isotope data in calculating present and paleo radioactive element distribution in the rock formations. The methodology involved in the determination of U loss in samples from an outcrop from sedimentary rock formation of Bambuí, Brazil, are illustrated in Figure 3. It provides a comparison of calculated (from Pb isotope data) and measured (mass spectrometric isotope dilution method) U content. The dashed line indicates the general trend.

Figure 4 is a plot of U loss with depth, indicating lower degrees of loss at greater depth. This trend may be due to groundwater activity or oxidizing conditions becoming more pronounced closer to the surface, thus making U more mobile. The stable isotope (C and O) data seem to support post depositional alteration (Iyer et al., 1995). It is clear that effects of U loss should be considered in calculations of radiogenic heat production. The dashed line indicates power law fit.

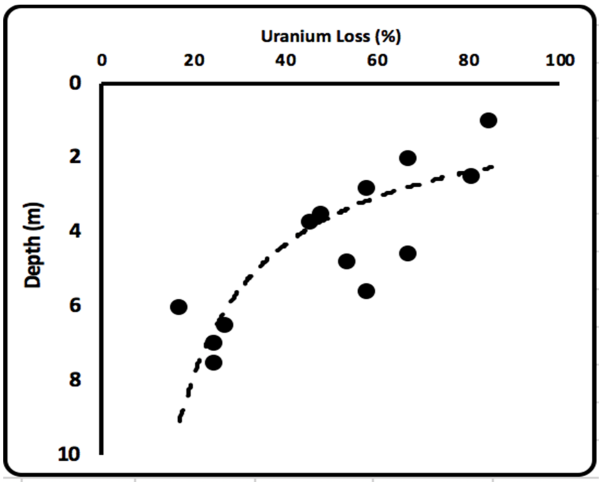

Figure 4 - Uranium loss (%) with depth (meters) below ground surface in samples from the MF 7 outcrop in the sedimentary rocks of Bambuí group, Brazil. The dashed line indicates polynomial fit.

4. Geothermal Model Considerations

The starting point for paleothermal model of SEDEX deposits is the standard equation for heat conduction in a medium with heat sources. The differential equation for temperature (T) distribution with depth (z), in a one-dimensional medium with thermal conductivity λ and heat production A, may be expressed as:

$$\frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) + A = 0 \qquad (1)$$

In order to obtain a convenient solution, one must take into consideration variation of λ with temperature and specify vertical distribution of radiogenic heat in crustal layers. For the sake of simplicity, we consider a model which allow for hyperbolic decrease of thermal conductivity with temperature and exponential decrease of heat production with depth:

$$\lambda(T) = \frac{\lambda_0}{1 + \alpha T} \qquad (2a)$$

$$A_0 = A_0^* \exp(-z/D) \qquad (2b)$$

Where λ_0 is thermal conductivity at temperature T_0, α its temperature coefficient, A_0^* paleo heat production at the initial uneroded surface and D its logarithmic decrement.

In developing models of the present crustal thermal regime of the crust available information on near surface heat flow, heat production and regional crustal structure are taken into consideration. The local topographic relief is small and available information on subsurface conditions do not seem indicative of high permeability strata at depth that would permit extensive groundwater flow systems. Thus, models based on the assumption of steady state conductive thermal regime should lead to reasonable estimates of subsurface temperatures for this region.

The available information on near surface heat flow, heat production and regional crustal structure were taken into consideration in developing models of the present thermal regime of areas of SEDEX deposits (Hamza, 2001). The results presented in figure 5 reveal that temperatures are high in areas of low heat productivity and/or high heat flow.

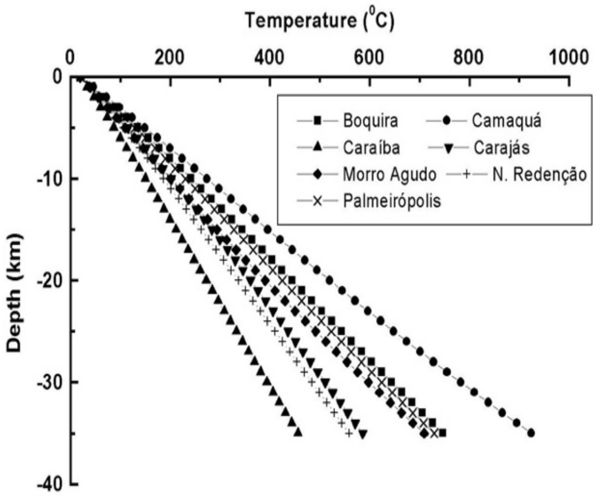

Figure 5 - Distribution of crustal temperatures in areas of sulfide ore deposits (Adapted from Hamza, 2001).

5. Inferences on Paleothermal Conditions

The development and maturation of a generic subseafloor hydrothermal system involves three stages. Starts with deep emplacement of subvolcanic intrusions, which occur below structures such as rifts or calderas. This results in shallow subseafloor alteration and associated formation of hydrothermal exhalative sediments. The second stage is characterized by intrusion of subvolcanic magmas and resultant generation of a deep-seated seawater convection system. Finally, development of a mature, large- scale hydrothermal system in which sub horizontal isotherms control the formation of semi conformable hydrothermal alteration assemblages. In many cases, the high-temperature reaction zone next to the cooling intrusion may undergo ruptures due to seismic activity or dyke emplacement, allowing focused up flow of metal-rich fluids to the seafloor and formation of SEDEX deposits.

Fluid inclusion data provide information on temperatures existing at the time of formation of SEDEX deposits. In other words, such data may be considered as representing P-T conditions existing at the depth levels in crustal layers. Hence, we may impose a convenient boundary condition as:

$$T = T_s \text{ at } z = z_s. \tag{3a}$$

$$T = T_0 \text{ at } z = 0. \tag{3b}$$

where T_s is the fluid inclusion temperature at depth z_s and T_0 temperature at the surface.

The equation for paleo heat flow (q_p) can now be written as solution to equation (1) subject to the conditions (2) and (3):

$$q_p(z) = \frac{\lambda_0}{z_s\,\alpha}\ln\left(\frac{u_s}{u_0}\right) + A_0 D - \left(\frac{A_0\,D^2}{z_s}\right)\left[1 - e^{-u}\right] \tag{4}$$

Note that the first term on the right-hand side of equation (4) represents the contribution of fluid flow process to paleo heat flow from the thermal event, referred to in the present work as the "SEDEX component". The remaining terms on the right-hand side represent the contribution of radiogenic heat. The relation for paleo temperature (T_p) may now be written as (Hamza, 1981; 1982):

$$T_p\,(z) = \left(\frac{1}{\alpha}\right)\left\{(1 + \alpha\,T_0)\exp\left[\left(\frac{\alpha}{\lambda_0}\right)\left(q_p\,z - A_0 * D\,z + A_0 D^2\,(1 - \exp(-z/D))\right)\right] - 1\right\} \tag{5}$$

Results of numerical simulations of heat flow associated with SEDEX systems at shallow depths are illustrated in Figure 6. As expected SEDEX systems at shallow depths have higher heat flow values compared to those at deeper levels. Another notable feature is that at small circulation depths the magnitudes of heat flow associated with fluid flow are larger by more than an order of magnitude relative to those of radiogenic component.

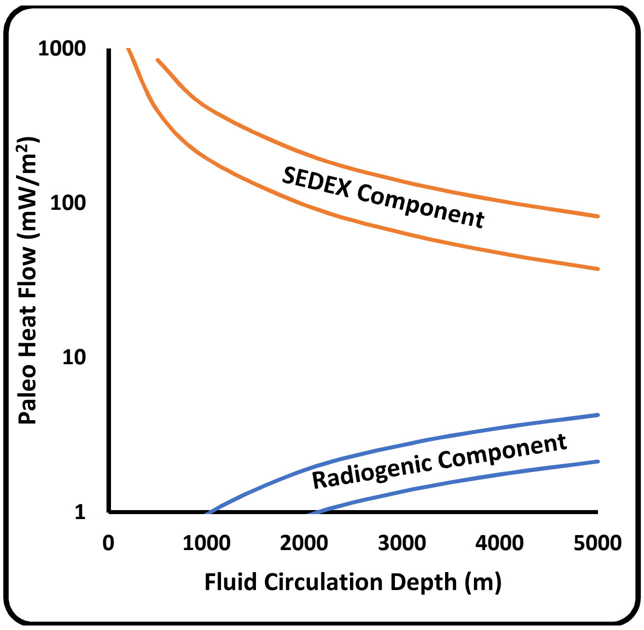

Figure 6 - Results of numerical simulations of heat flow in SEDEX systems.

Comparison of the temperature distribution in figure 6 with those obtained from studies of fluid inclusions and isotope variations of coexisting sulfides, indicate values of 20km for the depth of circulation of ore fluids. The estimates of depth are however sensitive to the value of heat flow employed in model calculations. The nature of relation between heat flow and the depth of circulation, illustrated in figure 7, reveal that heat flow in excess of 100mW/m^2 during metallogenic episodes (Hamza, 2001). Results of model simulations indicate that stretching accompanied by intra-crustal magma under-plating is the mechanism for high paleo heat flow.

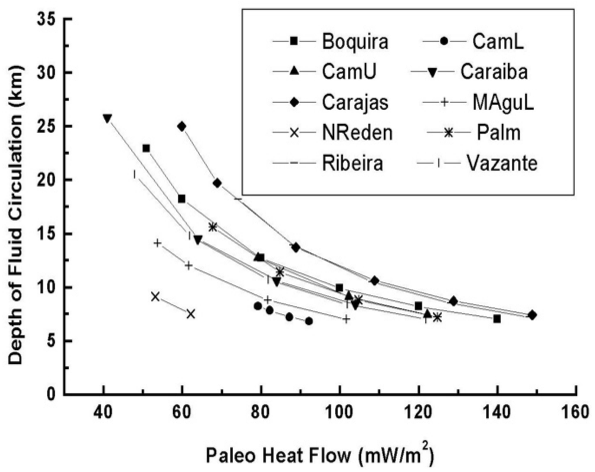

Figure 7 - Relation between depth of circulation of hydrothermal fluids and paleo heat flow in areas of sulfide ore deposits (Adapted from Hamza, 2001).

6. Spatial and Temporal variations

Formation of SEDEX deposits is intimately related to subsurface fluid flows in the local lithologic sequences. The main elements in such flow systems include interconnected zones of recharge, sub horizontal flow path and a discharge zone, as illustrated in the schematic of figure 8. Here the path AC represents the recharge zone, path CD the sub horizontal flow zone and the path DB represents the discharge zone.

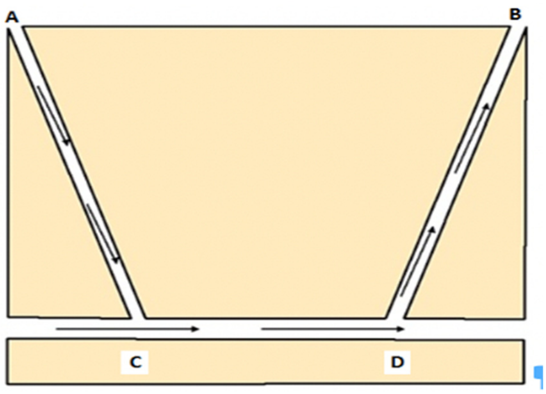

Figure 8 - Schematic representation of fault system in areas of SEDEX deposits. Path AC represents the recharge zone, CD the sub horizontal flow zone and DB the discharge zone (Adapted from Alexandrino and Hamza, 2010).

Results of numerical simulations reported in the work of Vieira et al (2013) may be adapted for understanding nature of temperature variations along such flow paths. The results of numerical simulations considered by Vieira et al (2013) indicates that the magnitude of temperature variations along the horizontal flow path is significantly larger than that in the recharge zone. As expected sharp temperature drops occur along the discharge zone

On the other hand, velocities of horizontal fluid movement are likely to be lower, a natural consequence of wider flow paths, larger permeability. These are conditions favorable for detention of fluid parcels along zones of lithologic changes and structural discontinuities. Thus, temperature data reported in fluid inclusion studies are most likely representative of geothermal regime along horizontal flow paths of SEDEX systems.

7. Discussion and Conclusions

The present study is an attempt to use the representative data of fluid inclusion temperatures and radiogenic heat production from thirteen areas of sedimentary exhalative (SEDEX) deposits of eastern Brazil, ranging in age from 0.65 to 2.85 by, to decipher the paleo heat flow.

The results obtained indicate heat flow in the excess of 80 mW/m2 in areas of mineral bearing sulphide ore deposits, during periods of ore forming processes. Such anomalously high heat flow are more than twice the present-day values for stable tectonic units of Precambrian age. There are indications that high heat flow values were sustained by circulation of hydrothermal fluids in the upper crust, during periods not exceeding a few hundred million years. The resulting geothermal episodes may be considered as constituting short-period "heat pulses" occurring in stable tectonic environments, generated by magma emplacements in the upper crust, leading to formation of areas of sulfide ore deposits. Model simulations indicate that subsidence episodes induced by stretching and magma under-plating constitute the mechanisms for high heat flow during the ore-forming processes. The mobility of radioactive element U yielding lower value of the paleo radiogenic heat production data, if the measured radioactive element data are employed, is pointed out. To surmount this problem, use of lead isotope data to calculate the present as well as paleo U and Th concentrations is suggested.

8. Acknowledgments

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