Deep crustal heat flow in the Tocantins Structural Province in Brazil: Inferences based on temperature dependence of compressional wave velocities

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Abstract

New insights into the thermal structure of Crust in Tocantins Structural Province in Brazil have been obtained based on heat flow data and temperature dependence of compressional wave velocities determined in seismic reflection profiles. This new approach, designated as the seismo-thermal method, is based on analytical solution to the standard heat conduction problem in stratified media coupled with empirical relations between seismic velocities and temperatures in crust-mantle interphase. The results reveal the presence of systematic trend of increasing mantle / sub crustal heat flow from eastern to the western segment of the Tocantins structural province.

Introduction

Understanding the deep thermal field of crustal segments is a relatively complex problem that require not only availability of suitable observational data for outlining temperature gradients and heat flux at shallow depths but also knowledge of geological structures and physical properties of the main subsurface layers. Geothermal measurements made in shallow boreholes provide information on near surface heat flux. Such data may be employed along with suitably selected crustal models in making inferences on deep crustal thermal conditions. However, considerable uncertainties exist in results of deep crustal temperatures derived from such models, which are essentially downward extrapolations of near surface thermal gradients and heat flow, the calculations of which assume suitably selected values of thermal conductivity and radiogenic heat production.

On the other hand, results of crustal seismic studies are capable of providing valuable complementary information related to the physical characteristics of deep crustal structures. Hence, integrated analysis of data acquired in seismic studies and geothermal investigations may be considered as the best approach in studies of deep crustal thermal fields. Of particular interest in this context is the analysis of the effect of temperature on seismic velocities. This problem has been addressed in several earlier studies (e.g. Kern and Richter, 1981; Goes *et al*, 2000; Shapiro and Ritzwoller, 2004; Kuskov and Kronrod, 2007; Perry et al, 2006; Vedanti et al, 2011). However, few studies to extract information about temperature from data of seismic velocities in the crust. Only the works of Cermak (1982) and Verdoya et al, (1998) comment indirectly this association.

In the present work, we report progress obtained in integrated analysis of geothermal and deep seismic reflection data for the structural province of Tocantins in the central parts of the Brazilian highlands.

Geological Characteristics of the study area

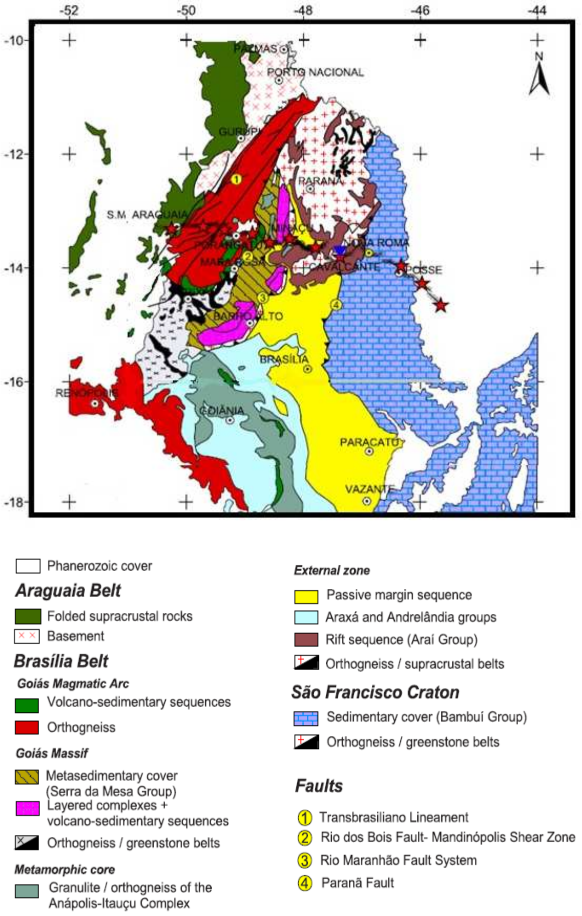

Figure 1. Geologic map of the central part of the structural province of Tocantins (Modified after Fuck, 1994).

The structural province of Tocantins may roughly be described as the Precambrian crustal segment between Archean cratons of Amazon and São Francisco (Almeida *et al* 1981). It consists of a system of orogens, characterized by folded regions and thrust zones, designated as Brasília, Paraguay and Araguaia belts. The origin of these structural elements is believed to be related to convergence and collisional episodes of three relatively large crustal segments, belonging to the Amazon craton in the west, São Francisco craton in the east and Paranapanema craton in the southwest (Almeida *et al* 1981). The geological context of the study area indicating the relative locations of major crustal blocks of the Tocantins structural province is illustrated in the map of Figure (1).

According to Fuck (1994), the main segments that constitute this province include areas of Phanerozoic sediment covers, Goias Massif, Magmatic arc of Goias and fold belts of Brasilia and Paraguai–Araguaia. Goias Massif is composed of Archean and Paleoproterozoic rocks, affected by thermos-tectonic events of the Braziliano orogenic cycle (Fuck, 1994; Fuck et al, 2002).

Crustal Seismic Studies

Results of seismic refraction profiles have been reported by Perosi (2006) along two profiles that cut across the central sector of the Tocantins structural province. In a follow up study Berrocal et al (2004) and Soares et al (2006) reported mean values of longitudinal (V_p) and transverse (V_s) wave velocities of crustal layers in the Araguaia belt, Goias Massif, regions of folds and thrust zones along the western parts as well as the rock sequences along the western border of the São Francisco craton. This is shown in figure (2).

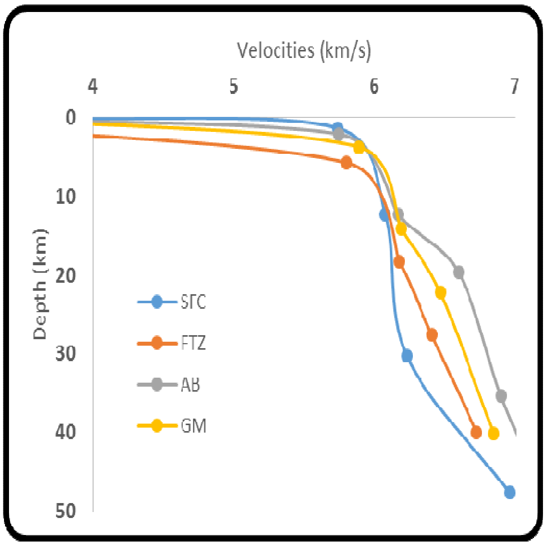

Figure (2) Vertical distributions of P wave velocities for the four main crustal segments in the study area.

The velocities are in the normal ranges encountered for continental crustal segments. The Sao Francisco craton (SFC) seems to be characterized by relatively low velocities while Araguaia belt (AB) have high velocities. Intermediate values of velocities are found for Goias Massif (GM) and the thrust and fold belts (TFB). The structure of crust is variable and have been interpreted based on two or three-layer models. There is some uncertainty as to the determination of the base of thick sedimentary sequences. These are often metamorphosed and become seismically indistinguishable from the crystalline rocks of the basement. Seismic velocities. In the middle crust (usually 5-15 km thick), usually composed of rocks in amphibolite facies, are $\sim 6.4 < VP < \sim 6.8$ km s^{-1}. P-wave velocities in the lower crust, believed to be of metamorphic rocks in granulite facies range from ~6.8 to ~7.2 km s^{-1}. In Precambrian shield and platform areas the lowermost crust have relatively high P-wave velocities ($\sim 7.2 < VP < \sim 7.6$ km s-1).

Data Base

The data sets employed in the present work include results of geothermal studies by Alexandrino (2008) for the São Francisco craton and by Vieira and Hamza (2014) for the state of Tocantins. Results of geothermal studies reported by Hamza et al (1978) refer to values of temperature gradients in 16 localities, covering regions of Goias Massif (GM) and regions of fold belts and thrust zones (TFB) in the Tocantins province. Following this Alexandrino and Hamza (2008) and Alexandrino (2008) reported temperature gradient and heat flow values for additional 36 sites of which 18 are situated in the São Francisco craton (SFC). The data set has been useful in deriving a new heat flow map of the State of Tocantins.

Methodology for studies of Deep Crustal Heat Flow

The availability of crustal seismic data has opened up the possibility for obtaining not only estimates of temperatures in the lower crust but also of the vertical distributions of thermal conductivity and radiogenic heat production in the main crustal layers. Empirical relations between seismic velocities and thermal parameters are usually employed for this purpose. In the absence of detailed knowledge of the vertical variations seismic velocities a discretized medium approach has been considered satisfactory. In such a scheme values of radiogenic heat production (*A*) and thermal conductivity (λ) are specified for each layer. Thus, for an n-layered medium with subscripts indicating layer number, A_0 and λ_0 represent values of the parameters at the surface (z = 0) and A_B and λ_B represent values at the base of the crust (z = z_b). Similarly T_0 indicate temperature at the surface and T_B that at the base of the crust. As shown in figure (3).

$z_0 = 0$	A_0	T_0	λ_0
z_1	A_1	T_1	λ_1
z_2	A_2	T_2	λ_2
z_3	A_3	T_3	λ_3
z_4	A_4	T_4	λ_4
z_B	A_B	T_B	λ_B

Figure 3 - Schematic representation of the simplified layered model for heat production and thermal conductivity in the study area.

The discretized medium approach was employed in determining vertical distributions of thermal conductivity, radiogenic heat production and basal temperatures of the main crustal segments of the study area. Brief summaries of results obtained are presented in the following items.

a) Thermal conductivity

Artemieva and Mooney (2001) have proposed typical values of thermal conductivity for common crustal layers based on seismic data. The values proposed take into consideration density and compositional variations. Values of thermal conductivity are known to vary with rock type, density and pressure. Figure (4) illustrates the vertical distributions of thermal conductivity, derived from seismic velocity distributions in four major crustal segments of the Tocantins geological province. Note that thermal conductivity decreases with depth in all crustal blocks.

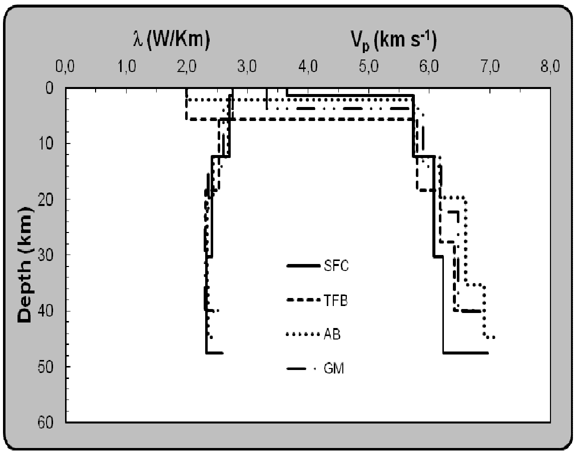

Figure 4. Vertical distribution of thermal conductivity (λ) and crustal seismic velocities (Vp) in the crust beneath São Francisco Craton (SFC), Araguaia Belt (AB), region of region of Thrust and fold belts (TFB) and Goiás Massif (GM). The right panel indicates the general trends.

b) Radiogenic Heat Production

Values of radiogenic heat production in crustal layers may be estimated using empirical relationships with seismic P wave velocities. In the present work, we have made use of the relation proposed by Kern and Siegesmund (1989) that is independent of the geological age. Figure (5) illustrate the vertical distributions of heat production derived from the seismic velocities, for the crustal segments of the Tocantins structural province.

Note that the near surface values vary from 1.18µW m^{-3} in Goiás Massif (GM) to 1.70µW m^{-3}, in Fold Belts and Thrust Zones (TBF).

At the lower crustal depths all crustal blocks have heat production values of less than 0.5µW m^{-3}.The general trends of vertical variations in heat production is illustrated in the right panel.

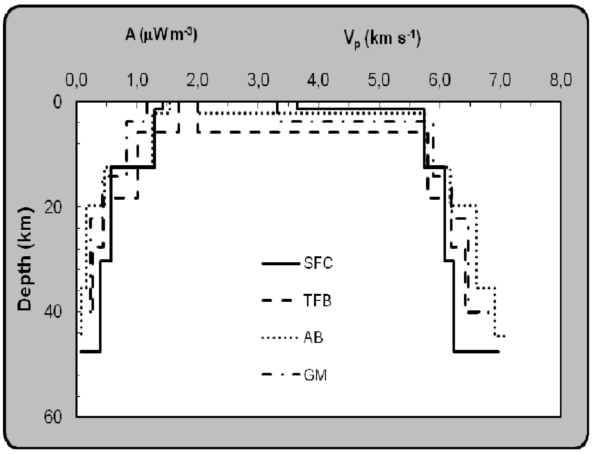

Figure 5. Vertical distribution of crustal seismic velocities (Vp) and computed values of heat production in São Francisco Craton (SFC), Araguaia Belt (AB), region of region of Thrust and fold belts (TFB) and the Goiás Massif (GM).

c) Basal Temperatures of Crustal Blocks

The nature of variation of seismic velocity with temperature and pressure have been discussed in several of the earlier works (Pasquale et al, 1990; Cermák et al, 1991; and Verdoya *et al.,* 1998) are based on the differences in values of in-situ seismic velocities with those measured in laboratory conditions as related to a correction factor that depends on temperature and pressure, It may be written as:

$$V_p\left(20^oC, 100MPa\right) - V_p\left(T,P\right) - B\left(T,P\right) = 0 \qquad (1a)$$

where V_P (20ºC,100MPa) is the velocity of compressional wave in km/s at 20^{o}C and at 100MPa pressure and V_P *(T, P)* is velocity of compressional wave in km/s at temperature (T) and pressure (P). B (T, P) is a correction factor evaluated at temperature T and pressure in P, both of which are functions of depth z in kilometer (km). The relation for B is:

$$B(P,T) = k_1\left[20 - T(z)\right] + \frac{k_2}{2}\left[400 - T^2(z)\right] - \frac{k_3}{k_4}\left\{\exp\left(-100k_4\right) - \exp\left[-k_4 P(z)\right]\right\} \qquad (1b)$$

where k$_1$, k$_2$, k$_3$ and k$_4$ are constants. The values of the constants in equation (4b) are given in Table (1).

Table 1. Mean values of the constants in equation - 1b (Verdoya et al, 1998).

Constants	Value	Units
k_1	-1.7×10^{-4}	km/s ºC
k_2	-6.0×10^{-7}	km/s ºC^2
k_3	8.8×10^{-4}	km/s MPa
k_4	2.39×10^{-3}	km/s MPa

d) Vertical distributions of temperatures

The results obtained in items (a), (b) and (c) discussed above has been employed in determining vertical distributions of temperatures in the main crustal blocks of the study area. The procedure adopted in calculations of temperature is based on the solution of the steady state heat conduction equation for a medium with heat sources and temperature dependent variations in thermal conductivity. The solutions for temperature that satisfy the boundary conditions that temperature are T_0 and T_B at the surface bottom boundaries may be written as:

$$T = T_{n-1} + \frac{(q_{n-1} - A_{n-1} D_{n-1})}{\lambda_{n-1}} (z - z_{n-1}) + \frac{A_{n-1} D_{n-1}^2}{\lambda_{n-1}} (1 - \exp(-(z - z_{n-1}) / D_{n-1})) \quad (2a)$$

The solution for flux is:

$$q = q_{n-1} - A_{n-1} D_{n-1} + A_{n-1} D_{n-1} \exp(-(z - z_{n-1}) / D_{n-1}) \quad (2b)$$

If independent estimates of basal temperatures are available (as for example estimates derived from seismic velocities) these may serve as additional boundary conditions for adjusting the estimated values of thermal conductivity (λ), heat production (A) and the scale factor (D). The solution presented in equations (5a) and (5b) has been widely adopted in deriving crustal geotherms (see for example, Blackwell, 1971; Hamza, 1982; Cermak, 1995). The main problem in such geotherms is the uncertainties model parameters, leading to widely different estimates of basal temperature and mantle heat flux. In the present work, we have adopted a solution to this problem by adopting basal temperature of the crust estimated from seismic velocities as an independent boundary condition. This procedure is in effect a coupling of the solutions presented in equations (1)) with those in equations (2) through iterative procedures. It has the advantage that the results derived using conventional geothermal studies may now be "tied" with results of seismic studies, which leads to considerable reduction in uncertainties. It is referred to in this work as the seismic – geothermal method (SGM).

Results

Crustal geotherms have been for the main crustal segments of the study area using the newly proposed seismic – geothermal method (SGM). The results obtained for the region of São Francisco craton is presented in Figure (6). This figure indicates the distribution of crustal temperatures for surface heat flow values in the range of 50 to 55mW m^{-2} and geothermal gradient of 18 to 20ºC km^{-1}. The corresponding basal temperatures are in the range of 707 to 804 °C.

The Figure (7) indicates the vertical distributions of thermal conductivity, geothermal gradient and heat flow. Note that there are substantial reductions in geothermal gradients and heat flow with depth in the crust. The mantle heat flow is estimated between 28 and 34mW m^{-2} for a mean basal temperature of 760 °C.

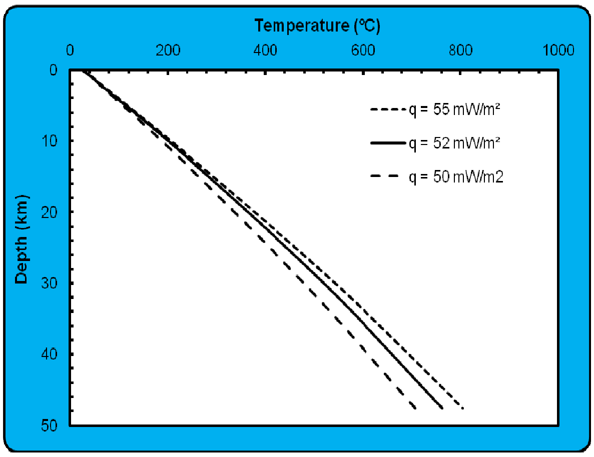

Figure 6. The temperature distribution in the regions of sedimentary cover (near the São Francisco craton). sedimentary covers.

In Figures (8) and (9) we can observe the results for the heat flow and geothermal gradient in surface for the region of the Goiás Massif. The flow is between 50 and 55 mW m^{-2}, the gradient geothermal between 17 and 20 ºC km^{-1}. The temperature, heat flow and geothermal gradient in the crust of the base are respectively: 656 to 741 °C; 34 to 39 mW m^{-2} and 15 to 17 ºC km^{-1}.

This result is important to validate the method because the well site coordinates which were carried out temperature measurements (-48.36W and -13.51S) is located on the Porangatu line at the time in region Goiás Massif, because the heat flow and geothermal gradient estimated by traditional methods are quite similar to those values. Thus, we have, therefore, the first scientific evidence of the validity of this new technique of geothermal research.

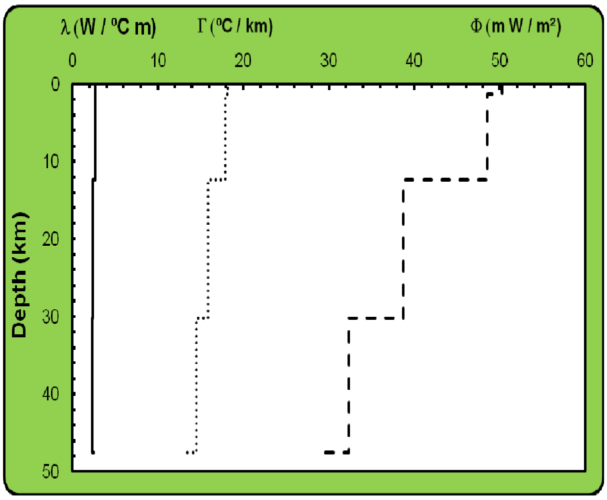

Figure 7. Crustal geotherms of the region of sedimentary cover (near the São Francisco craton). Heat flow (Φ), geothermal gradient (Γ) and thermal conductivity (λ)

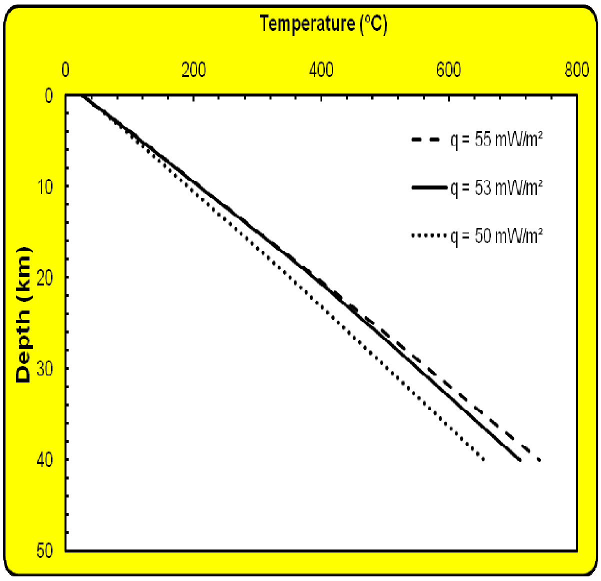

Figure 8. The temperature distribution in the regions of Goiás Massif.

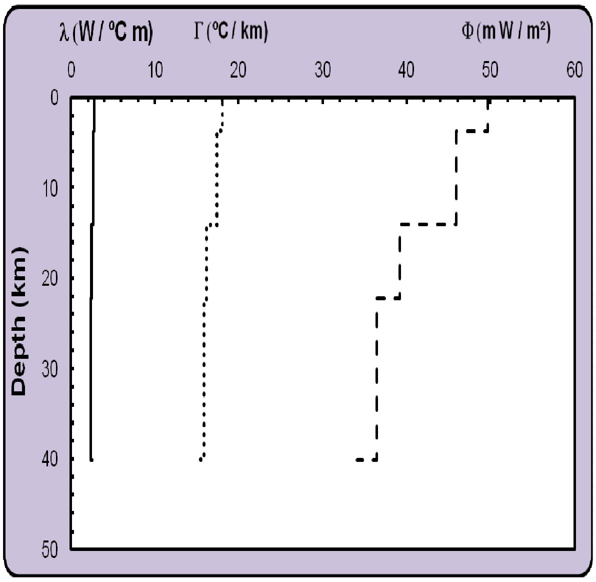

Figure 9. Crustal geotherms of the region of Goiás Massif. The legend is the same as that of figure (7).

The thermal structure of the region of the region of Thrust and fold belts is shown in figures (10) and (11). The figure (10) shows the temperature variation with depth. The value of the basal temperature is between 618 and 690 °C.

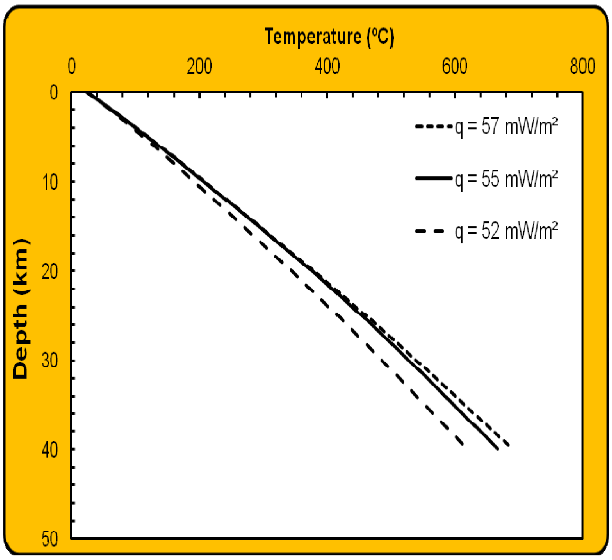

Figure 10. The temperature distribution in the regions of Thrust and fold belts

Since the figure (11) shows the behavior of the heat flow, geothermal gradient and the thermal conductivity in depth. On the surface the value of the heat flow and geothermal gradient region were estimated in 53 to 57mW m^{-2}, 17 and 20°C km^{-1} and in crustal base 30 to 34 mW m^{-2} and 12 to 15 ºC km^{-1}.

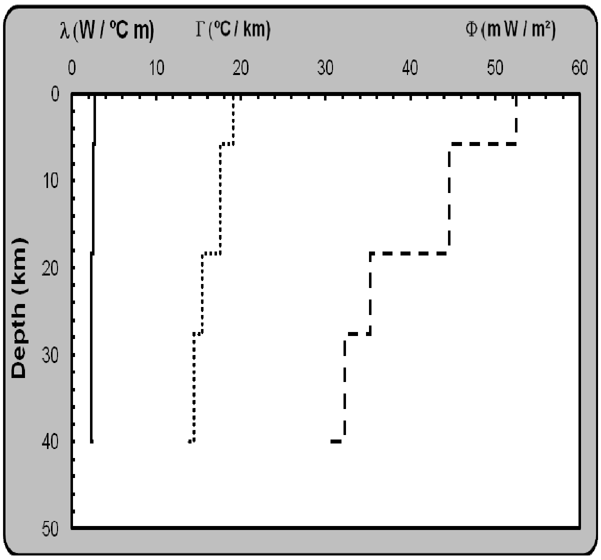

Figure 11. Crustal geotherms of the region of Thrust and fold belts (Niquelândia). The legend is the same as that in Figure (7).

Figures (12) and (13) shows the results obtained for the heat flow and temperature distribution, for region Araguaia Belt. In the figures we can observe that the heat flow varies of 43 to 48 mW m^{-2}, the geothermal gradient is between 15 and 17 °C km^{-1} in surface.

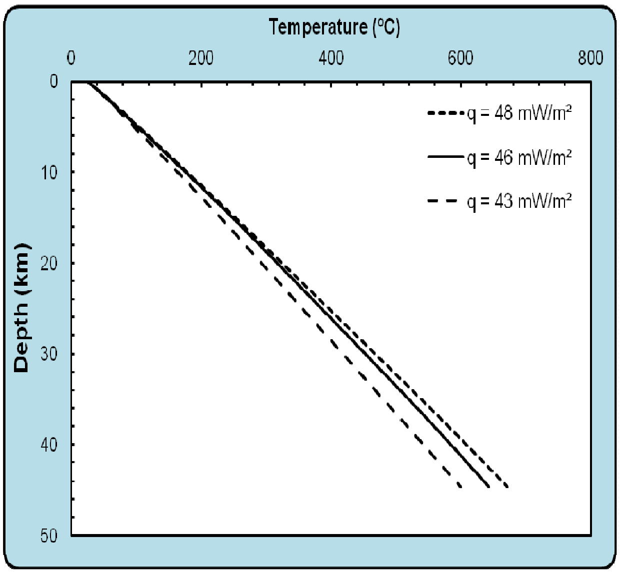

Figure 12. The temperature distribution in the region Araguaia Belt.

In base crust the minimum value for temperature is 599 ºC and maximum de 672 °C, the range of heat flow is 28 to 33 mW m^{-2}, since the value of the geothermal gradient is 12 to 14 °C km^{-1} in the crust of the base.

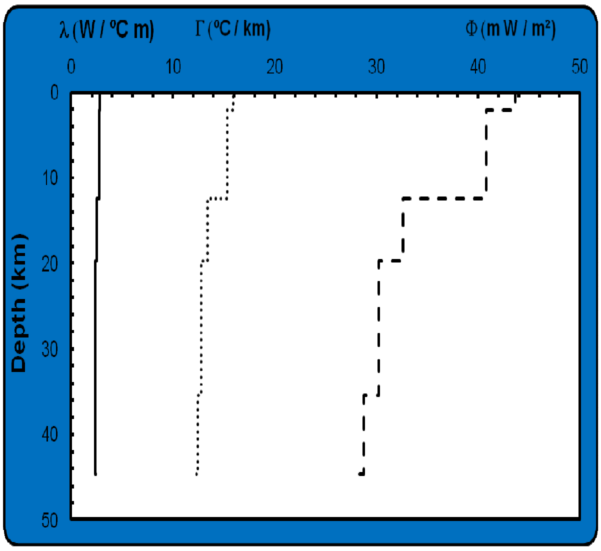

Figure 13. Crustal geotherms of the region Araguaia Belt. The legend is the same as that in Figure (7).

Conclusions

The present results show that it is possible to infer the temperature from seismic wave velocities in the crust layers, especially in the lower crust, due to a greater homogeneity compared with the upper crust.

The estimated values for the flow of heat, geothermal gradient on the surface and the heat flow, geothermal gradient and temperature at the base of the crust by the proposed method in this paper, called Seismic-Geothermal Method (SGM) are similar to the estimated values by Conventional Geothermal Method (CGM). Moreover the results obtained by both methods are consistent with information available in the literature. This fact serves to validate the technique described in this work. However, we still need to carry out a larger number of test to we can validate this new technique.

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