Research Article

Thermomagnetic Features of Crust in Southern Parts of the Structural Provinces of Tocantins and São Francisco, Brazil

Suze Nei P. Guimaraes and Valiya M. Hamza

Observatório Nacional, Rua General José Cristino 77, Rio de Janeiro, CEP 20921-400, RJ, Brazil

Correspondence should be addressed to Valiya M. Hamza; hamza@on.br

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In the present work we report results of a regional scale investigation of the thermal and magnetic characteristics of the crust in the southern sector of the geologic provinces of Tocantins and São Francisco, Brazil. Updated compilations of aeromagnetic and geothermal data sets were employed for this purpose. Use of such techniques as vertical derivative, analytic signal, and Euler deconvolution in analysis of aeromagnetic data has allowed precise locations of the sources of magnetic anomalies and determination of their respective depths. The anomalies in the Tocantins province are considered as arising from variations in the magnetic susceptibilities and remnant magnetizations of alkaline magmatic intrusions of the Tertiary period. The lateral dimensions of the bodies are less than 10 km, and these are found to occur at shallow depths of less than 20 km. On the other hand, the anomalies in the cratonic areas are related to contrasts in magnetic properties of bodies situated at depths greater than 20 km and have spatial dimensions of more than 50 km. Analysis of geothermal data reveals that the cratonic area is characterized by geothermal gradients and heat flow values lower when compared with those of the Tocantins province.

1. Introduction

The geotectonic provinces of São Francisco and Tocantins are often considered as the main structural units in the eastern part of the South American platform [1, 2]. Geological and geophysical studies performed to date have allowed mapping of structural and tectonic features near the surface of these structures, but little is known about the vertical distributions at depths in the crust.

One of the convenient ways of circumventing this difficulty is to evaluate aeromagnetic survey data and compare the results with those of geothermal studies. According to available information [3, 4] past attempts to integrate the results of aeromagnetic surveys were limited to incorporating standard corrections of technical operations. It became clear that a detailed review of aeromagnetic survey data is needed, focusing on the judicious use of corrections (leveling and microleveling, eliminating the effects of diurnal variation and the internal field) and use of advanced techniques of interpretation (vertical derivative, analytic signal, and Euler deconvolution). Also, “suture” techniques need to be

employed in integration of data from several surveys in this area in obtaining a coherent analysis of the subsurface geological significance of the results and its correlations with structural features. Another parallel objective of this work has been comparison of maps of the residual anomalies of magnetic and the geothermal fields in the area of study as a means of obtaining complementary information on the thermal state of the upper crust in the study area [5].

2. Geological Characteristics of the Study Area

The study area comprises the southern parts of the structural provinces of Tocantins and San Francisco, located in the east-central parts of the South American platform. The map in Figure 1 illustrates the geological characteristics of the study area. Basement rocks of Archean age outcrop mainly in the southern and southeastern parts. Isolated blocks have also been identified in the northwestern parts. Most of the remaining area is covered by metamorphic complexes of Proterozoic age. Phanerozoic sediment cover occurs as a set

FIGURE 1: Simplified geological map of the southern São Francisco and Tocantins provinces (modified after IBGE, 2010).

of discontinuous blocks in the east-central parts and also in the western part of the study area.

The São Francisco structural province is a tectonically stable region, where the main geological structures have ages ranging from Mesoarchean to Paleoproterozoic [6–8]. The southern limits of this province are determined by the fold belts of the Brazilian orogeny. The Tocantins structural province is situated in the western segment of the study area. The crustal blocks in this province are composed of granitic-gneissic-granulite compartments (Goiás Median Massif) of Archean to Neoproterozoic age and metasedimentary rocks (Araguaia, Brasília, and Uruaçu belts) of Proterozoic age. A characteristic feature of this province is the presence of a significant number of alkaline magmatic intrusions of the Tertiary period. There are also indications of the occurrence of large number of nonoutcropping intrusions [9].

According to results of seismic studies [10] the thickness of the upper crust in the region of study area is 40 km in the São Francisco craton and 32 to 42 km in the Brasília belt and adjacent areas. In the Ribeira belt, located in the southern part of the study area, the crustal thickness is found to be 37 km.

3. Materials and Methods

3.1. Aeromagnetic Database. The data used in the present work is based on results of aeromagnetic surveys carried out in the study area. The earliest of these, known as Project 1009, refer to surveys carried out during 1971 and 1972 as part of Geophysical Accord between Brazil and Germany. The results of this survey, acquired initially in analog form, were later digitized by Paterson, Grant & Watson Ltd. (PGW) and Western Mining Company (WMC). These digital data sets, made available for academic research by Company of Mineral Resources Research (CPRM), were acquired for purposes of the present work. According to available information the surveys were carried out during the years of 1971 and 1972.

FIGURE 2: Areas covered in the three different aeromagnetic surveys of the study area.

The nominal flight height for data acquisition was 150 m and spacing of flight lines was 2 km. The preferred direction of survey lines of this project was east-west. Integration of these data sets demanded a tedious and time-consuming work of incorporating the needed corrections and unification in the early stages of processing. The areas covered by these surveys are shown in Figure 2.

The database of the present work also includes results of geophysical surveys of the state of Goiás, carried out during the years of 2004 and 2005. This data set, made available for academic research by Superintendent of Geology and Mining (SGM) of the state of Goiás, was also acquired in the present project. High-resolution equipment for data acquisition was used in this survey, which also employed modern positioning techniques such as GPS (global positioning system). The flight height is 100 m, with line spacing of 500 m. The dominant direction of survey lines was north-south. Data was also acquired along control lines with spacing of 5 km, along directions perpendicular to the main survey lines. Data with this quality are considered as belonging to high-resolution group.

3.2. Data Processing Techniques. The bulk of aeromagnetic data processing in the present work was carried out using the computer software package Geosoft Oasis Montaj. Built-in facilities of this package allowed homogenization of the database and elaboration of maps, making use of standard procedures of interpolation, gridding, and plotting methods [11]. The package was also used for setting geographic coordinates, which in the present work are referenced to as the datum SAD-69. The results obtained at this stage of data processing were found to be in reasonable agreement with the

FIGURE 3: Residual magnetic field of the study area.

maps already published by CPRM in 2003 [3] and by SGM in 2009 [4].

The next step in data processing has been removal of the International Geomagnetic Reference Field (IGRF) from the records of the total field. This has been an important part of data processing in view of the significant time differences in data acquisition and the large area extent of the surveys. The main problem with the published models of IGRF is that it is meant to serve all areas of geomagnetism and, as such, is not specifically tailored to the needs of the exploration community. Hence two different approaches were adopted. In processing data from Project 1009, acquired during the decade of 1970, we used the algorithm developed by the Geomagnetism Group at the National Observatory (Rio de Janeiro, Brazil). This algorithm, which makes use of historic records of magnetic data from permanent stations and several hundred temporary stations in Brazil, provides a better representation of local magnetic field. It has often been considered as providing good correlation with low latitude geomagnetic data. As for the data of the geophysical survey of Goiás, acquired during the period of 2004 to 2005, we used the built-in IGRF reference fields, available in the software package Geosoft Oasis Montaj.

The removal of the field originating in the core of the Earth and the external variations occurring mainly in the ionosphere and the sun allows derivation of the field of crustal origin. This crustal field was corrected for *heading* and incorporated into an ensemble of corrected data sets. Filters were then applied to correct directional trends. In addition, leveling and microleveling corrections were carried out to eliminate distortions of flight lines [12].

3.3. Geothermal Data Base. Current understanding of the thermal field of subsurface layers in the geologic provinces of Brazil is based mainly on results of heat flow studies, analysis of physical and chemical characteristics of thermal springs, and assessments of geothermal resources, carried out since 1970 [13–18]. Parts of this information have been gathered and organized as a modern database by the Geothermal Laboratory of the National Observatory in Rio de Janeiro.

This database refers to geothermal measurements at 1212 localities in the Brazilian territory. According to this compilation geothermal measurements have been carried out at 135 localities in the study area.

The values of geothermal gradients and heat flow in this database include those derived from results of direct measurements as well as indirect estimates. Several methods have been employed depending on the nature of primary geothermal data [15, 19]. Among these, we highlight the following.

3.3.1. Conventional: CVL [20]. This is the classical method in which temperature gradient is calculated by least square fit to borehole log data, within selected depth ranges. The use of this method is best suited for cases where the local rock formations are laterally homogeneous and have constant thermal properties. It is also important that influences of processes (such as drilling disturbances, groundwater flows, local geologic structures, and climate change effects) which induce thermal perturbations at the site are absent.

3.3.2. Bottom Hole Temperature: BHT [21]. This method makes use of bottom-hole temperatures measured in deep oil wells for determination of apparent geothermal gradients and heat flow. The data are usually corrected for disturbing effects of drilling activity.

3.3.3. Geochemical Estimates: GCL [22]. The principle of this method is based on the argument that abundances of certain chemical elements dissolved in thermal waters provide indirect information on the temperatures of geothermal reservoirs. This data along with inferences on subsurface geological structures allows estimates of geothermal gradients and heat flow at sites of thermal springs.

Hamza and Muñoz, 1996 [15], and Gomes and Hamza, 2005 [19], have provided detailed information on the use of these methods and assessment of quality and reliability of the results obtained. Standard methods are employed in interpolation and gridding of geothermal data and in deriving maps of geothermal gradients and heat flow. A major problem with the geothermal database is its relatively low data density, a limitation arising from the well-known practical difficulties in acquiring field data. Thus geothermal maps are generally useful only for identifying regional trends, but lack resolution needed for identification of small-scale structures and near surface features.

4. Results Obtained

4.1. Residual Magnetic Field. On conclusion of the correction procedures of the data sets, described in Section 3.2, techniques of *suture* were employed in unifying the corrected data sets [23]. This technique unites the data sets with a minimum of distortion along their contact boundaries, making smooth interpolations of trends present in their interior parts. The results obtained at this stage were used in deriving the map of the residual magnetic field (also called anomalous magnetic field) of the study area, illustrated in Figure 3. Referring to

FIGURE 4: Analytic signal derived from the crustal magnetic field. Numbers refer to anomalies in the residual field, indicated in the map of Figure 3.

the map of this figure we note that there are considerable variations in the intensity of the crustal field in the study area, with both negative (lower than 100 nT) and positive values (higher than 100 nT). Most of the large-scale variations with sharp changes between positive and negative values are associated with geologic structures at relatively shallow depths. Locations of nine such structures are indicated in the map of Figure 3.

Comparison with the geology map of Figure 1 reveals that most of the large magnitude positive anomalies are situated in areas of outcrops of basement rocks. A notable exception to this trend is the SE-NW belt of anomalies cutting across the São Francisco province. This is the preferred direction of many of the structural features in the South American platform. According to geological studies, metamorphic belts along this direction are marked by expressions of intense deformation, crustal accretion, and reworking [24] which explain this strong magnetic manifestation. Hence the possibility that a belt of basement rocks occurring beneath the thin cover of Proterozoic rocks contributes to the occurrence of such anomalies cannot be ruled out. Most of the negative anomalies are found to occur along parallel belt, cutting across the southern part of Tocantins province and northern part of the São Francisco province. Some isolated negative anomalies also occur in the southeastern parts of the São Francisco province. Additional information on the tectonic context of such structures is given in the list of Table 1, which also includes maps of the individual anomalies.

4.2. Analytic Signal. Another technique used in interpretation of aeromagnetic data is the analytic signal [25–27], which is basically the magnitude of the second derivative in the three directions of the magnetic field. In practice, the analytical signal is regarded as the best tool for locating the edges of bodies that have magnetic contrast. When applied to the residual field magnetic anomaly the responses highlight the surface boundaries of geological bodies with contrasts in

FIGURE 5: Map of the vertical derivative of crustal magnetic field. The blue lines represent the lineaments inferred from the distribution of vertical derivatives.

magnetic properties relative to the surrounding rocks. Hsu, 2002 [28], suggests use of second and even higher order derivative to better highlight the bodies. However, higher orders enhance the noise leading to unrealistic solutions, especially when dealing with low quality data sets.

The geographic distribution of analytic signal for the data of the present work is illustrated in the map of Figure 4. It is clear that there are substantial variations in the magnitude of the analytic signal, the maximum value being 0.1 nT/m. As expected, most of the variations occur in localities of residual magnetic anomalies, indicated in the map of Figure 3 and listed in Table 1. These are considered as indicative of bodies with contrasts in magnetic properties and located at relatively shallow depths. A zone of low values of the analytic signal is found to occur in the north-central parts of the study area. But its interpretation is difficult in view of the lack of suitable data in the adjacent area to the west.

4.3. Vertical Derivatives. Following the common practice in interpretation of aeromagnetic data the technique of spatial derivative (see, e.g., Gunn, 1975 [29]) has been employed in the present work. The objective has been to highlight the features associated with high frequency variations in the residual magnetic field and mitigate features associated with low frequency variations. The map of vertical derivative of the study area is illustrated in Figure 5.

Note that the features in this map appear as linear magnetic minima, edges, and dislocations in the local field. Some of them appear as ridge-like features in the map of vertical derivatives. The geographic distributions of such ridges are found to be linear in many cases and following standard practice have been classified as magnetic lineaments. The mechanisms responsible for the connectivity of magnetic lineaments are believed to be the changes in magnetic properties and brittle behavior of the geological formations from the action of local tectonic forces [30, 31].

A total of 67 lineaments were identified. Some of the major regional lineaments are indicated in the map of Figure 5. Most of lineaments are found to be predominantly

TABLE 1: Localities and tectonic context of prominent anomalies of the residual magnetic field. Color codes of residual anomalies are given in the inset of Figure 3.

Identification	Locality	Tectonic context	Residual anomaly
1	Caldas Novas	Tocantins province. Basic intrusion in area with thermal springs.
2	Patrocínio	Tocantins province. Alkaline intrusion with remnant magnetism.
3	Pedrinópolis	Tocantins province. Intense anomaly in metamorphic fold belt.
4	Araxá	Tocantins province. Alkaline intrusion with remnant magnetism.
5	Itabirito	São Francisco province. Area with extensive iron ore deposits.
6	Pirapora	São Francisco province. Basic intrusion of the Espinhaço sequence.
7	Santa Fé de Goiás	Tocantins province. Located in the Magmatic Arc of Goiás.
8	Poços de Caldas	Tocantins province. Area with extensive iron ore deposits.

TABLE 1: Continued.

Identification	Locality	Tectonic context	Residual anomaly
9	Catalão	Tocantins province. Alkaline intrusion with remnant magnetism.

FIGURE 6: Depth of the anomalous magnetic sources from Euler deconvolution results.

in the NE-SW direction, coincident with the preferred directions identified in the geological surveys (e.g., Blum [32]). These are found to cross the two structural provinces of Tocantins and São Francisco, which has also been identified in geological studies (e.g., Heilbron and Machado [33]).

4.4. Euler Deconvolution. The Euler deconvolution technique [34] employed in this work has the objective of extracting information about the depths of magnetic sources. The result is independent of the direction and inclination of the main magnetic field and the orientation of the magnetic sources. Thus, the method is relatively insensitive to small-scale distortions of the field. A total magnetic anomaly (T) without correction of regional values produced by a set of three-dimensional sources satisfies the homogeneous field equation of Euler:

$$(x - x_0) \frac{\partial}{\partial x} T + (y - y_0) \frac{\partial}{\partial y} T + (z - z_0) \frac{\partial}{\partial z} T = -\eta T, \quad (1)$$

where x_0 , y_0 , and z_0 are the initial coordinate positions of the anomalous source and η is the structural index as defined in [34].

Following the practice adopted in the literature the variations in the degree of homogeneity of the field are associated with a set of structural indices, which specifies the type of magnetic source. According to Thompson [26] a structural index of zero represents contact between different types of

rocks, while indices of 0.5 and 1 represent, respectively, linear features such as faults and dykes. Also, the structural indices 2 and 3 are indicative of cylindrical and spherical structures, respectively. The success of the method is evaluated in a qualitative way, through accumulation of solutions associated with the different indices.

In an attempt to minimize biased interpretations in determining the depths, the following guidelines were adopted in the use of this technique.

- (1) The established limit for uncertainty in the depth value, calculated by the Euler equation, is 10%.
- (2) The magnetic anomalies modeled are dipolar features, consistent with the current knowledge of deep geological structures. Since the focus of the study is on regional scale variations, we follow the practice of Hsu [28] and use the structural index three in the solution of Euler equation.
- (3) The size of the interpolation window of the program used to calculate the Euler deconvolution is 15 km. According to standard practice this value of window size corresponds to sources of 3 to 6 km extension.

The results obtained indicating the depths of sources are illustrated in the map of Figure 6. In the present case, the map derived is based on results of using the *krigrid* interpolation method [23], with a grid spacing of 0.5 degrees (~55.7 km). The grid-averaged depths of anomalous magnetic sources are in the ranges of 10 to 50 km, as indicated in the color scale of this figure.

Note that the depths of bodies in the north-west sector of the Tocantins province and in the southeastern portion of São Francisco craton are in the range 10 to 20 km. On the other hand, the depths of bodies in northern parts of the São Francisco province and in the southern parts of the Tocantins province are in the range of 25 to 50 km. There are indications that the systematic differences in the depths of magnetic sources arise from mechanisms related to the thermal regime of the crust.

4.5. Maps of Geothermal Gradients and Heat Flow. The geothermal data compiled in the present work has been employed in interpolation of values with grid spacing of 0.5 degrees (55.7 km). The maps of geothermal gradients and terrestrial heat flow derived from the gridded data sets are illustrated in Figures 7(a) and 7(b). Also indicated in these maps are localities of geothermal measurements.

The geothermal gradient map (Figure 7(a)) reveals a zone of relatively high values (greater than 18°C/km) along

FIGURE 7: Maps of geothermal gradient (a) and heat flow (b) in the study area. The black dots indicate localities of geothermal measurements.

a narrow belt in the western and extreme southern parts of the Tocantins province. On the other hand, the São Francisco province is characterized by relatively low thermal gradients in the range 10 to $18^{\circ}\text{C}/\text{km}$. The heat flow map of the study area shown in Figure 7(b) reveals features similar to those of the geothermal gradient. Thus, heat flow values in excess of $50 \text{ mW}/\text{m}^2$ occur along narrow belts in the western parts of the Tocantins province, whereas most of the São Francisco province is characterized by heat flow values of less than $50 \text{ mW}/\text{m}^2$. Comparative analysis of features discernible in Figures 6 and 7 points to an inverse correlation between thermal and magnetic characteristics of the study area. Thus, areas of high geothermal gradients and heat flow are characterized by sources of magnetic anomalies at relatively shallow depths and vice versa.

5. Discussion and Conclusions

The present work constitutes a regional scale investigation of the thermal and magnetic characteristics of the crust in the southern sector of the geologic provinces of Tocantins and São Francisco, Brazil. Use of such techniques as vertical derivative, analytic signal, and Euler deconvolution in analysis of aeromagnetic data has allowed a better understanding of the sources of magnetic anomalies and estimates of their respective depths. There are indications that anomalies in the Tocantins province arise from variations in the magnetic susceptibilities and remnant magnetizations of alkaline magmatic intrusions of the Tertiary period. The lateral dimensions of the bodies are less than 10 km, and these are found to occur at shallow depths of less than 20 km. On the other hand, the anomalies in the cratonic areas are related to contrasts in magnetic properties of bodies situated at depths greater than 20 km and have spatial dimensions of more than 50 km. Analysis of geothermal data reveals that the cratonic area is characterized by geothermal gradients

and heat flow values lower when compared with those of the Tocantins province. There are indications of an inverse correlation between thermal and magnetic characteristics of the study area. Thus, areas of high geothermal gradients and heat flow are characterized by sources of magnetic anomalies at relatively shallow depths and vice versa.

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