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THERMAL AND MAGNETIC CONTEXT OF CENTRAL BRAZIL STRUCTURES: A STUDY OF MAGNETIC LINEAMENTS IN THE CENTRAL PORTION OF THE TRANSBRASILIANO LINEAMENT AND ADJACENT REGIONS

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ABSTRACT. Analysis of thermomagnetic features of the region in central Brazil based on aeromagnetic data. Edge enhancement techniques of anomalous magnetic field (AMF) were employed for this purpose. This approach has allowed the identification of magnetic lineaments in subsurface associated with structural features like the Transbraziliano lineament (TBL). The depth estimates of these structures were obtained by means of spectral analysis of AMF. The results revealed the existence of several near-linear magnetic features in the region between 48-51ºW and 12-14ºS. The spacing of the magnetic lineaments, on the other hand, differentiates the region in two aspects: western (5-10km) while eastern (10-50km). Such differences have been considered indicative of changes in the thermal crustal distribution and deep-seated tectonic processes. Results of magnetic data analysis with heat flow variation indicated that the depth of magnetic sources inferred falls in the interval of 35-50 km. In the Tocantins structural province (TP), underlying the TBL, the depth intervals between the Curie and Moho surfaces differ by about 10 km, implying that only the upper parts of the crust are magnetized. On the other hand, in the region of the São Francisco Craton (SFC), this difference is much lesser (<2 km), indicating that almost all the crust is magnetized.

Keywords: magnetic lineaments; edge enhancement techniques; lineament spacing; spectral analysis; heat flow.

RESUMO. Análise das feições termomagnéticas da região do Brasil central com base em dados aeromagnéticos e geotérmicos. Foram empregadas para esta finalidade técnicas de aprimoramento de borda de campo magnético anômalo (AMF). Esta abordagem tem permitido a identificação de lineamentos magnéticos em subsuperfície associados a feições estruturais como o Lineamento Transbrasiliano (TBL). As estimativas de profundidade dessas estruturas foram obtidas por meio de análise espectral do AMF. Os resultados revelaram a existência de várias feições magnéticas quase lineares na região entre 48-51ºW e 12-14ºS. O espaçamento dos lineamentos magnéticos, por outro lado, diferencia a região em dois aspectos: oeste (5-10km) e leste (10-50km). Tais diferenças têm sido consideradas indicativas de mudanças na distribuição crustal térmica e processos tectônicos profundos. Os resultados da análise dos dados magnéticos com variação do fluxo de calor indicaram que a profundidade das fontes magnéticas inferidas cai no intervalo de 35-50 km. Na maior parte da província estrutural do Tocantins (TP), subjacente ao TBL, os intervalos de profundidade entre as superfícies de Curie e Moho diferem em cerca de 10 km, implicando que apenas as partes superiores da crosta são magnetizadas. Por outro lado, na região do Cráton do São Francisco (SFC), essa diferença é bem menor (<2 km), indicando que quase toda a crosta é magnetizada.

Palavras-chave: lineamentos magnéticos; técnicas de realce de borda; espaçamento dos lineamentos; análise espectral; fluxo geotérmico.

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INTRODUCTION

The focus of aeromagnetic surveys in Brazil has traditionally been associated with prospection of mineral and hydrocarbon deposits at shallow depth in the upper crust. Very few attempts have been made in using aeromagnetic data as a tool for investigating structures at deep crustal levels. Guimarães et al. (2014) employed spectral analysis of aeromagnetic data for examining tectonic characteristics and their implication for the vertical distribution of magnetization of deep crustal layers. Recently this approach has also been employed in the study of the depth distribution of magnetized crustal blocks in the adjacent cratonic region by Guimarães & Hamza (2019).

The area selected for the present study is localized between the longitudes 48º and 51º West and latitudes 12º and 14º South. A prominent tectonic feature present in this area is the Trans-Brazilian lineament (TBL). In the current investigation, we consider features in the vertical derivative (VD) of the residual magnetic field using shading techniques (Blakely, 1996) and examine variations in the density distribution of the lineaments in the study area. In addition, its relationship with the occurrence of thermal springs of central Brazil was also considered as well its implications for features in the depths of these sources by spectral analysis of residual magnetic field.

Geologic Context of the Study Area

The geologic context of the study area provided here is based mostly on information provided in the geologic map of CPRM (2014), Fuck et al. (2017) and De Morisson Valeriano (2017). According to De Almeida et al. (1973), the eastern part of the study area is part of the São Francisco Craton which has been tectonically quiescent since Archean times, while the western part is composed of fold belts which has been active in Neoproterozoic times, during the Brasiliano Orogeny. This orogeny resulted in the deformation of the crystalline basement and Neoproterozoic covers (Dardenne et al., 2000; Valeriano et al., 2004; Fuck et al., 2017; De Morisson Valeriano, 2017). The regional distribution of these geological units is illustrated in the simplified geologic map of Figure 1.

Many cratonic areas in the western and eastern part are covered with Phanerozoic sediments making it difficult to verify the nature of the deep crustal structure. The Tocantins structural province (TP) has been considered in geologic studies to be composed of rock formations belonging to the Araguaia fold belt and Goiás Massif in the western sector and to the Brasilia belt in the eastern sector. The eastern and western flanks of this province have undergone subsidence relative to the central sector. The sequence of inferred structural sequences is illustrated in the legend of Figure 1. The structural features of the eastern part of the study area are indicated in the map of Figure 2. Note that details of the structures in the area of the SFC are limited.

The western flanks of the region are covered by belts of Phanerozoic covers (especially the Brasília and Araguaia belts) which host geothermal anomalies, as observed in heat flow maps of Brazil (Vieira, 2015). These are formed by geologic units known as the inner zone of the Araguaia fold belt, Estrondo group and orthogneiss manifested as a result of the Brazilian Cycle (700-450 Ma). Part of the Goiás Magmatic Arc of Neoproterozoic age lies in the central areas of the study area. Also, the Goiás Massif of the Archean/Paleoroterozoic ages constitutes important structural sequences in the eastern part the study area. The eastern flanks are limited by the Tocantins province characterized by the orthogneisses of Neoproterozoic age and greenstone belts (Archean) of the Brasília belt, and by the São Francisco Craton. The limits of these units are marked by rock formation of the Bambuí group (Neoproterozoic age).

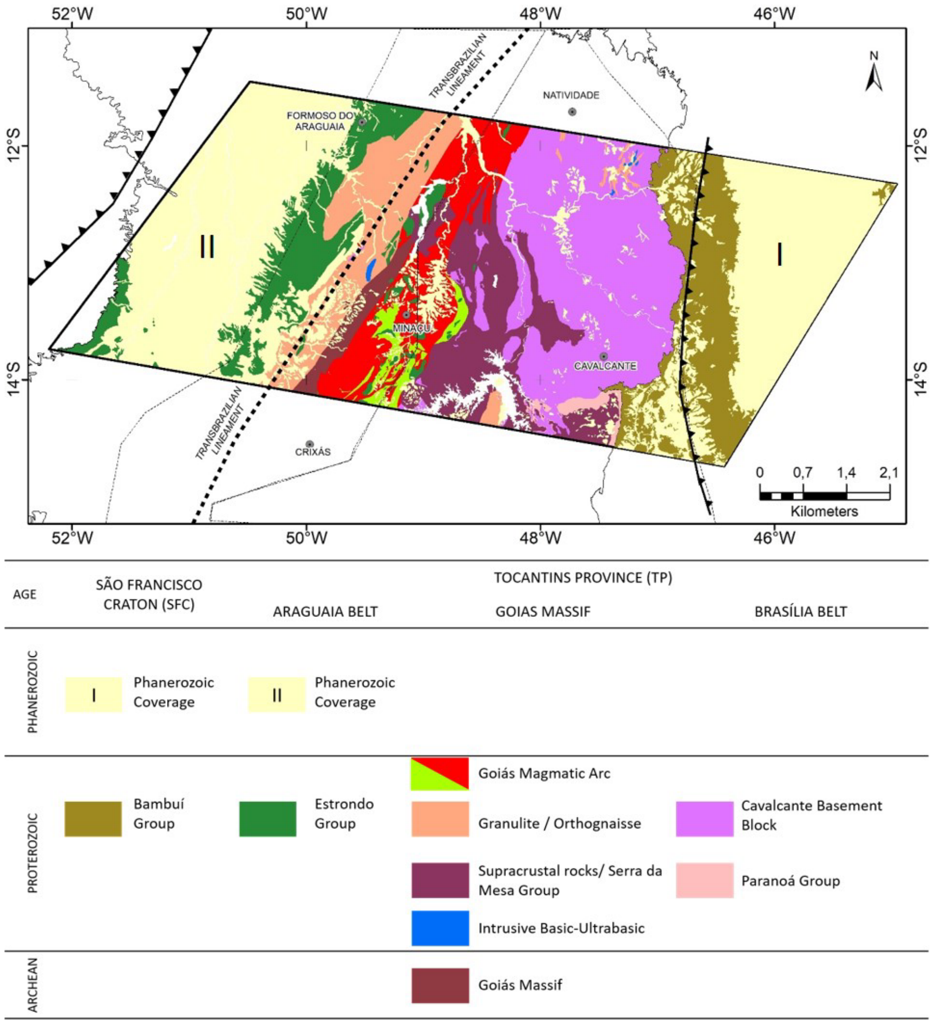

Figure 1 - Simplified geological map of the study area (Modified from Fuck et al., 2017).

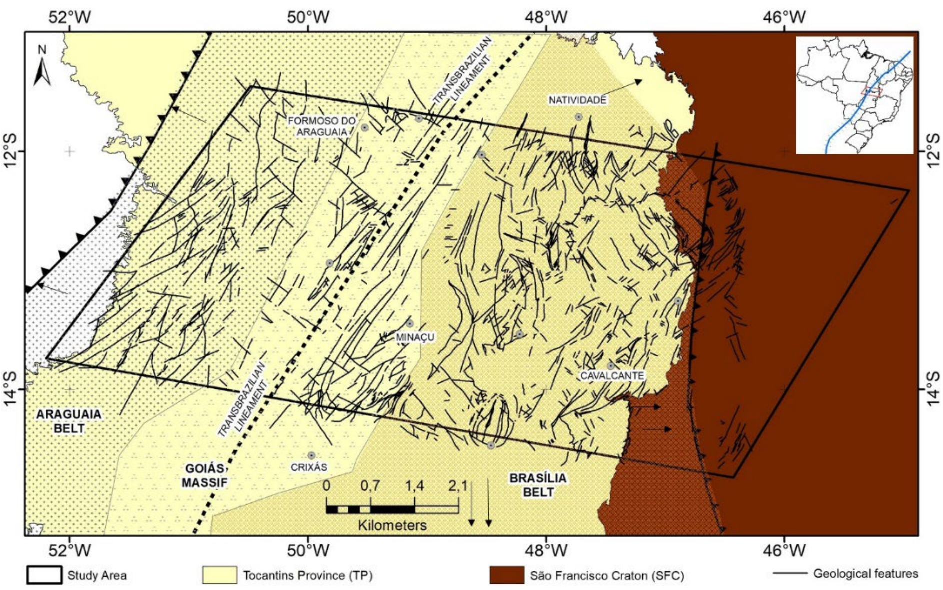

Figure 2 - Simplified map of structural elements identified in the study area. The black dotted line in this figure indicates the location of the Transbraziliano lineament (TBL) (modified by Cordani et al., 2016).

METHODS AND DATA ACQUISITION

The aeromagnetic data employed in this work are based on results of works compiled under the projects designated as Brazil-Canada Geophysical Project (PGBC), Magmatic Arc Mara Rosa (MAMR - Area 2), Paleo-Neoproterozoic of northeast from Goiás (PNNG - Area 5), Tocantins (TO), Complement of Tocantins (CTO), Rio Formoso (RF) and São Francisco Project (SF). These are public domain datasets, made available by CPRM (2014) for academic research purposes. The area extents of these datasets are provided in the map of Figure 3. In this figure, the blue polygon refers to the location of the study area. Project codes with relatively large coverage are 4021 in the east and 1020 in the west. Note that the TBL, indicated by the black dashed line, mostly cuts across the area of project 1020.

Additional details of these datasets are provided in Table 1. These include numerical project codes, year of acquisition, data types, flight altitude, spacing of flight lines, direction of flight routes and tie system for data control. Also it is included the information on tie system employed in data processing and sampling frequency (in seconds).

Different types of processing techniques were applied depending on the characteristics of the database. Initially, corrections were made for levelling, micro-levelling and filtering. These were followed by removal of diurnal and principal parts of the geomagnetic field. The second stage was based on the International Geomagnetic Reference Field (IGRF), which allowed determination of the residual or anomalous field components. For data collected after the year 2000, the anomalous magnetic field was acquired with standard corrections and levelling procedures applied. Following this step, suture techniques were employed to generate a unified dataset. The degree of coherence of this data processing step was verified by the application of directional filters. The parallelogram of the segment selected for analysis of lineaments is also indicated. The blank areas of the polygon indicate regions that have not been contemplated in the datasets.

The map of the anomalous magnetic field $(\overrightarrow{B})$, in units of *nano*Tesla (nT), obtained after the stage of routine corrections, is presented in Figure 4. A region of relatively high residual magnetic field intensity, with magnitudes in excess of 20 nT, occurs in the central part of the study area. Note that the TBL seems to mark the western boundary of this anomaly.

The used spectral analysis program (routine in MATLAB) enables changes in size of the search windows, allowing calculation of the depth of magnetic sources in different parts of the study area. The following interpretive geophysical techniques were used to analyze the aeromagnetic data: upward continuation, edge enhancement (vertical derivative, horizontal derivative, tilt derivative, analytic signal amplitude), and spectral analysis.

RESULTS AND DISCUSSION

Magnetic lineaments

In the current investigation, techniques that enhance vertical derivatives were applied using the computation package made available by the Oasis Montaj software (Geosoft, 2006). The result indicated that large parts of the magnetic lineaments, identified by means of vertical derivative analysis, occur around the TBL. Most of these lineaments are oriented NE-SW. They are indicated as continuous lines in red colour in Figure 5.

The removal of the background pattern of vertical derivatives provides a better view of the characteristics of spacing between the lineaments, as illustrated in Figure 6. In this figure, note that the lateral spacing of such lineaments is relatively small, ranging between 5 km and 20 km, around the TBL. The presence of such closely spaced anomalies was considered as an indication that the geologically defined TBL in the study area is in reality composed of a set of parallel quasi-linear fracture zones. Similar features are also observed in the lineaments of the region between the TBL and the SFC. Nonetheless, their spacing is relatively larger, of the order of 10km. The directions of these fracture

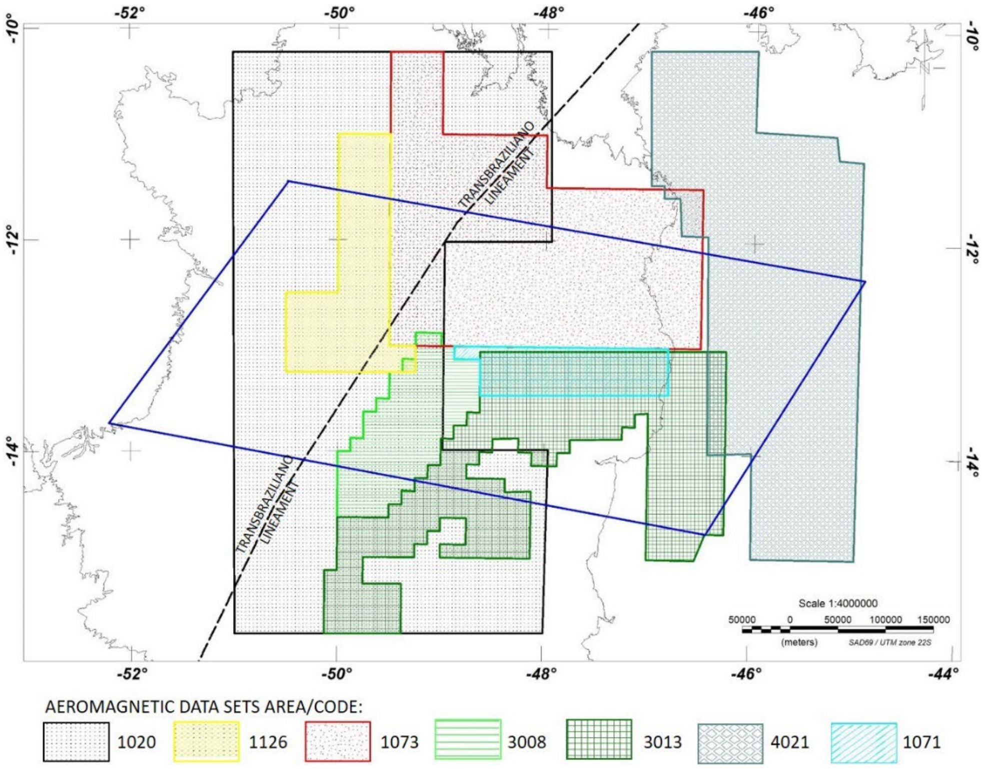

Figure 3 - The geographic extent of aero geophysical projects considered in this work. The numbers in the legend refer to codes of projects according to CPRM (2014). The blue polygon refers to the location of the study area.

Table 1 - Characteristics of datasets used in this study. The letters in the first column line refer to names of the project codes; in the following line there are the years of data acquisition.

DataSet	PGBC	MAMR	PNNG	TO	CTO	RF	SF
Code	1020	3008	3013	1073	1071	1126	4021
Year of Data Acquisition	1976	2004	2006	2006	2007	2014	1980
Spacing of Flight Lines	2 km	500 m	500 m	500 m	500 m	500 m	6 km
Tie Spacing	14 km	5 km	5 km	10 km	10 km	10 km	12 km
Direction of Lines	N-S	N-S	N-S	N-S	N-S	N-S	N-S
Tie Direction	E-W	E-W	E-W	E-W	E-W	E-W	E-W
Flight Altitude	150 m	100 m	100 m	100 m	100 m	100 m	125 m
Sampling Frequency for Survey	1s	0.1s	0.1s	0.1s	0.1s	0.1s	0.1s

Abbreviations used: N - north; S - south; E - east; W - west; km - kilometers; m - meters; s - seconds.

zones are likewise oriented *NE-SW*, albeit in the northern region a small change in the lineaments can be perceived to the east, while in the south part of the area, some lineaments feature a *NW-SE* direction.

According to Gholipour et al. (2016), the differences in fracture spacing may have arisen from changes in deep tectonic processes. It is also noteworthy that fracture zones are absent in the cratonic region on the eastern side of the study area. This was considered as an indication that the cratonic area may be comprised of relatively unbroken structural elements with practically no significant contrast in their magnetic properties.

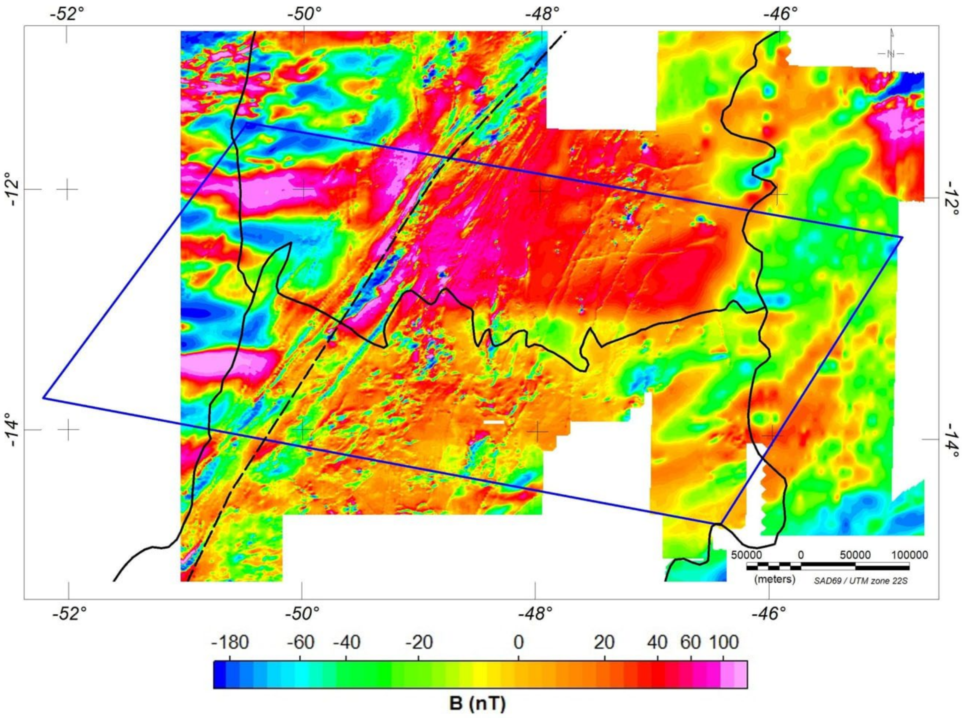

Figure 4 - Anomalous magnetic field map $\vec{B}$.

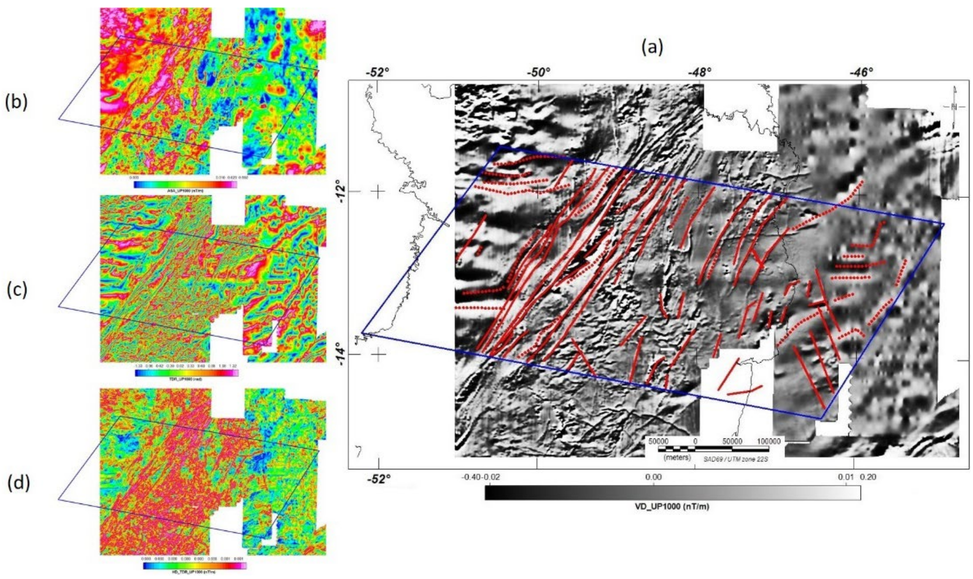

Figure 5 - Mapping of magnetic lineaments identified using edge enhancement techniques: (a) Vertical derivative (VD); (b) Analytic signal amplitude (ASA); (c) Tilt derivative (TDR); and (d) Horizontal derivative (HD). The continuous lines in red color refer to magnetic lineaments with greater reliability. The dotted lines indicate lineaments with relatively lower degree of reliability.

Inferences of the deep crustal structure

Results of spectral analysis of crustal magnetic field obtained from airborne survey data were also used to infer depth values of subsurface anomalous magnetic sources. This allowed additional insights into some fundamental aspects of the tectonic history of geological units in the study area. Such deep crustal structures (Fig. 7) were considered based on vertical variations in depth to the base of crust (designated here as Moho depth). Corresponding depths are considered in the current work as indicative of depth to isotherm of 580ºC. Distances to this isotherm were designated as depths of Curie temperatures.

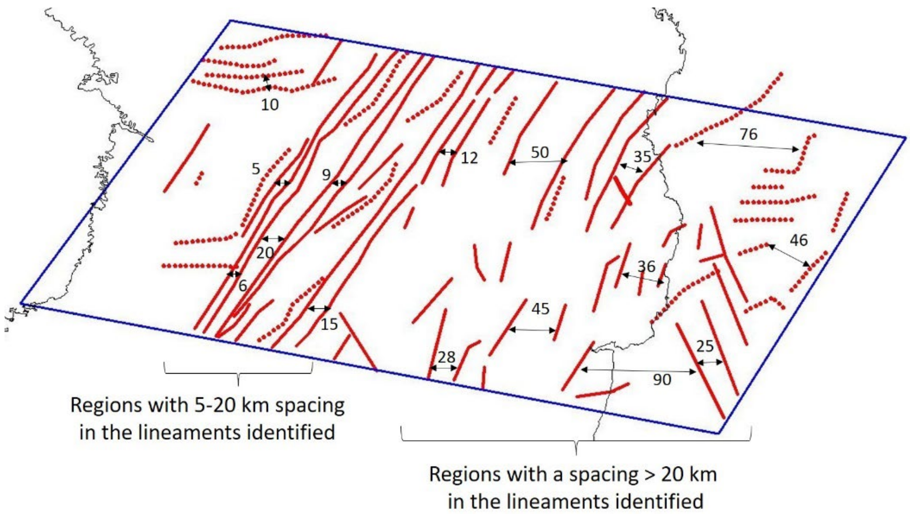

Figure 6 - Map illustrating spatial variations in fractures spacing identified using vertical derivative techniques.

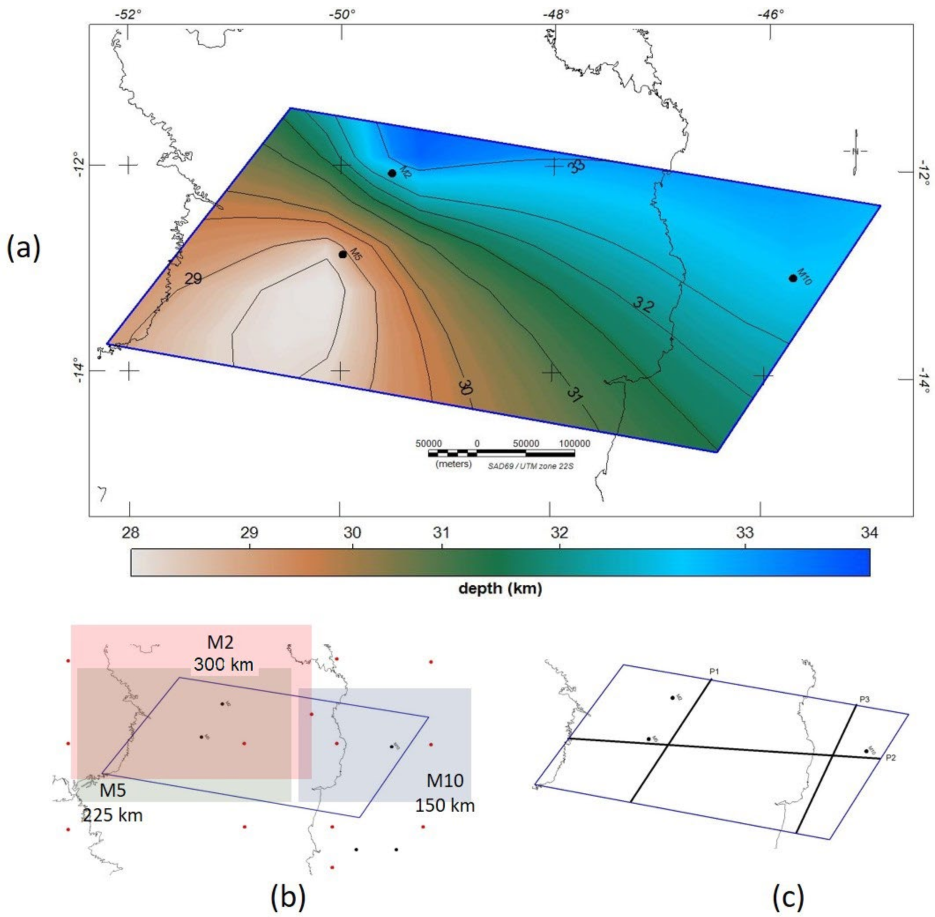

Figure 7 - (a) Spatial depth distribution of the magnetized crust, designated here as Curie surface map, of the study area. The depth values were calculated using the bottom of the deepest layer by the spectral analysis method. The curves represent isoline depths. (b) Arrangement of the spectral analysis windows of the study area. The black points described as M2, M5 and M10 (see Table 2) refer to the centroid point of the area. (c) Disposition of three profiles selected (P1, P2, and P3) for detailed investigation.

As a consequence of limitations in data availability, only three different investigation windows could be employed. These have a dimension of 150, 225, and 300km. The centroid method used in this study allowed the identification of magnetized sources as per their wavenumber range. These layers were recognized as shallow, intermediate and deep. The results obtained are presented in Table 2. With the thickness values for the magnetic layers acquired in the study area, the estimated depths to Curie surface vary between 42 km and 55 km, with the shallow layer limited to 2 km depth in thickness. These values were employed for calculating the depth to bottom of the deepest layer by the spectral analysis method. Figure 7 illustrates this subsurface arrangement of the magnetized crust, designated here as Curie surface.

Table 2 - Depth (in kilometers) of the top and the bottom of magnetic layers obtained in spectral analysis by the centroid method.

ID Windows **(km)**	**LON (W)**	**LAT (S)**	**Shallow**	**Mean**	**Deep**
			Top/ Bottom	**Top/ Bottom**	**Top/ Bottom**
M2 (300)	49.52	12.08	0.42	0.97	16.03
			0.83	3.67	33.30
M5 (225)	49.98	12.87	0.43	1.08	12.63
			0.87	5.77	28.28
M10 (150)	45.74	13.05	0.14	3.66	17.79
			1.88	6.76	32.79

Crustal geothermal profiles

The heat flow map derived from the geothermal analysis obtained by Hamza e al. (2020) is illustrated in Figure 8. It is clear that heat flow values are relatively high in the area of the NE-SW trending lineaments.

Three geothermal profiles were considered, as indicated in Figure 8. The first one (designated P1) has NE-SW direction, between longitudes 50ºW and 48ºW, and coincides with the TBL. It is situated in the western part of the study area. The second one (designated P2) is a W-E profile cutting across the structural provinces of Tocantins (TP) and São Francisco (SFC). The third one (designated P3) has NE-SW direction, between the longitudes 47ºW and 46ºW, within the SFC.

The values of depths to base of crust (Moho depth) along these profiles are based on results reported in seismic studies of the region (Assumpção et al., 2013). Geothermal resources considered to be of high enthalpy are tied to heat flow values greater than 80 mW/m^2 (Vieira, 2015; Hamza et al. 2020) in the Brazilian tectonic context.

Variations of Moho and Curie depths along the middle profile (P2) are shown in Figure 9. It reveals the presence of a major heat flow anomaly, with its peak located on the eastern side of the TBL. There are no corresponding anomalies in the Curie depth and also in the Moho. The fact that the heat flow anomaly is offset with respect to the TBL implies that the fracture system of the TBL is not vertical, but steeply inclined. It also implies that the process responsible for the heat flow anomaly is situated at shallow depths in the upper crust. It is possible that this heat flow anomaly is responsible for the occurrence of thermal springs in this region. It is evident that there is a prominent heat flow anomaly in the region between the TBL in TP and SFC.

The variations of the Moho and Curie depths and the heat flow in the other profiles listed above (P1 and P3) are illustrated in Figures 10 and 11, respectively. There are no indications of thermal anomalies in these two profiles.

The profile P3 (Fig. 10) is located within the São Francisco Craton. The rocks that make up this area basement are mostly Archean and consequently all the accumulated heat in the rock formation has already dissipated and the region may currently be considered as of low heat flow. The values for heat flow in this profile are not greater than 50 mW/m^2. Additionally, it is evident that heat flow variations are much lesser subdued along the northern (P1) and southern (P3) parts of the study area.

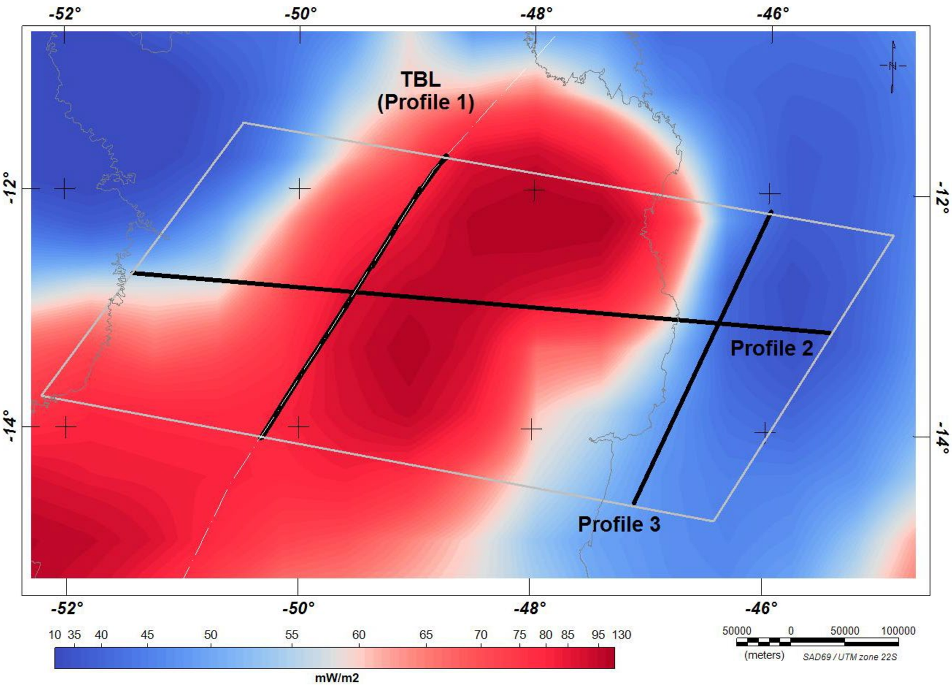

Figure 8 - Heat flow map of the study region. The black lines indicate the profiles selected (P1, P2, and P3) for detailed investigation.

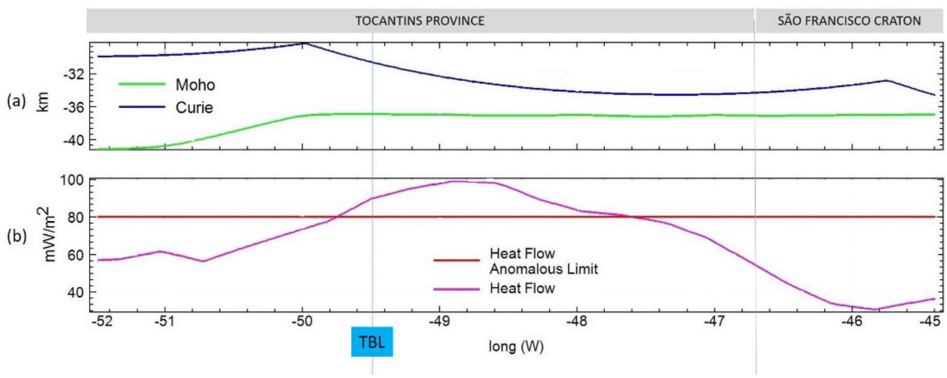

Figure 9 - Lateral variations in the (a) Curie surface and Moho depth; (b) heat flow along the profile (P2) in the central region, *WE* direction of the study area. The location of this profile is indicated in Figure 7c.

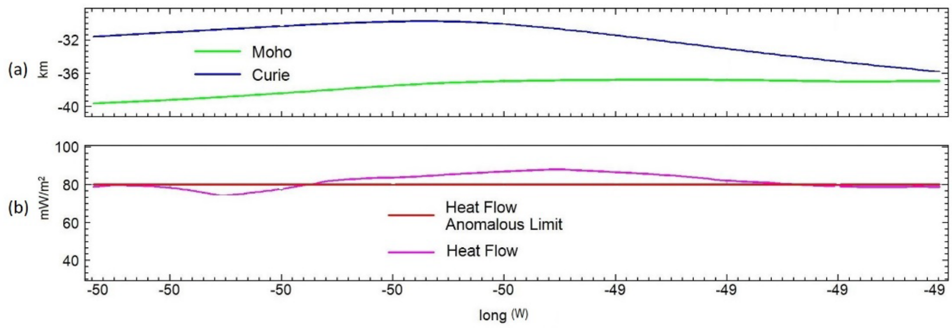

Figure 10 - Lateral variations in the (a) Curie surface and Moho depth; (b) heat flow along the Profile (P1) in the region of the TBL, *NS* direction of the study area. The location of this profile is indicated in Figure 7c.

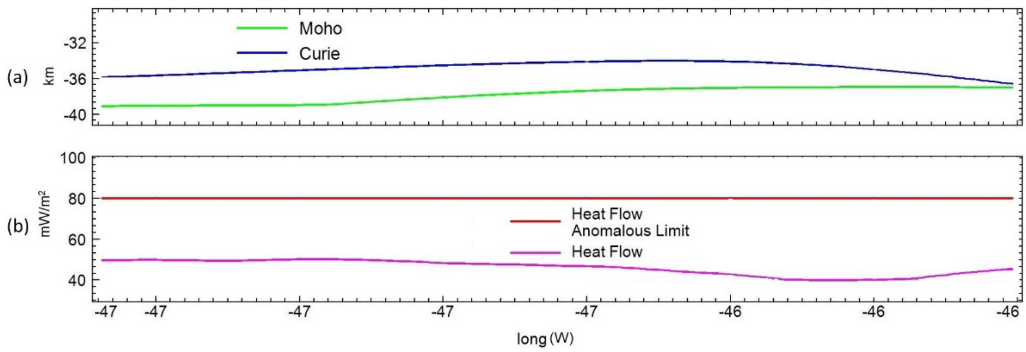

Figure 11 - Lateral variations in the (a) Curie surface and Moho depth; (b) heat flow along the Profile (P3) in the region of the SFC, *NS* direction of the study area. The location of this profile is indicated in Figure 7c.

CONCLUSIONS

The results obtained in this work reveal the existence of a set of near-linear magnetic features in the region between longitudes 48ºW and 51ºW and between latitudes 12ºS and 14ºS. Edge enhancement techniques applied to anomalous magnetic field and spectral analysis have allowed identification and characterization of magnetic lineaments. Along the western side of the study area, the spacing of magnetic lineaments ranges from 5km to 10km. In contrast, along the eastern segment of the study area, the spacing of fracture zones ranges from 10km to 50km. This difference in the spacing of fracture zones has been considered an indicative of changes in the nature of deep-seated tectonic processes.

The source depth inferred from the spectral analysis technique in the region spans from 35km to 50km. These results are in accord with those obtained through seismic refraction in Soares et. al. (2006). In most part of the Tocantins province underlying the TBL, the thickness between the Curie and Moho surfaces differs about 10km. On the other hand, in the SFC region, this difference is much lesser (<2km), evidencing that almost all the crust is magnetized.

The region between the TP and the SFC has moderate micro-seismic activity (Soares et. al., 2006) and recent studies point to anomalous geothermal conditions in the upper crust. However, direct evidences on the occurrence of magmatic intrusions at shallow crustal levels are absent. In the current work, we suggest the possibility that features identified in the aeromagnetic survey are indicative of fracture systems, which allow up-flows of carbonic fluids transporting geothermal heat. The presence of flows of carbonic gas (CO_2) has been observed at sites of thermal springs in this region (Coelho and Moura, 2006; Padilha et al., 2013; Abdallah, 2016; Solon et al., 2018) and reveals that the geothermal anomaly observed associated with alkaline igneous bodies resulted from amalgamation events in the magmatic arc (520 Ma ago).

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