Thermal and Magnetic Context of Central Brazil Structures: A study of magnetic lineaments in the central Trans-Brazilian Lineament (TBL) and adjacent regions.

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Abstract

This paper reports on the progresses obtained through the analysis of thermomagnetic features of the region between the southern part of Tocantins state and the northern part of Goias state, in Central Brazil. For that, we made use of data collected through aeromagnetic surveys. Techniques of shading applied to vertical derivative of Anomaly Magnetic Field (AMF) have been used to identify magnetic lineaments. The depth estimates of these structures were obtained by means of spectral Analysis of AMF (Centroid method). The results reveal the existence of a set of near-linear magnetic features in the region between the longitudes of 48^0W and 51^0W and between the latitudes of 12^0S and 14^0S. This is also an area of moderate microseismic activity and recent studies indicate anomalous geothermal conditions at the upper crust. However, direct evidences of the occurrence of magmatic intrusions at shallow crustal levels are absent. We postulate the hypothesis that the features identied as a result of aeromagnetic survey are indicative of fracture systems, thereby enabling the ow of carbonic uids observed at the region's thermal springs and transporting geothermal heat.

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Rio de Janeiro, December, 2020

Dear Chief Editor and Editorial Committee

As corresponding author I am pleased to submit you our complete manuscript entitled **"Thermal and Magnetic Context of Central Brazil Structures: A study of magnetic lineaments in the central Trans-Brazilian Lineament (TBL) and adjacent regions"**, for its consideration as paper in ***JGR-Solid Earth***.

This paper would not have materializes without the contributions of Dr. Fábio Pinto Vieira and Dr. Valiya M. Hamza, both at the National Observatory in Rio de Janeiro.

This paper presents results of thermomagnetic analysis in the central region of Transbrazilian Lineament on the Tocantins Provinces and in the cratonic region (Western part of São Francisco Cráton). This analysis made it possible considerations about the thermal context of formation the structural lineaments in surface and the magnetic lineaments in subsurface.

We made a special attention in keeping the correct style and format for JGR. We have no conflicts of interest to disclose. We thus hope you will find our submission acceptable for publication and take this opportunity to thank you for your considerations of this manuscript and the invitation from editorial committee to publication this work that in your resumed form initially was sent to international congress as expanded summary. We remain available for any suggestions you or the reviewers might have.

Yours sincerely,

Dra. Suze Nei Pereira Guimaraes

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Key Points:

- magnetic lineaments
- vertical derivative
- lineament spacing
- spectral analysis
- heat flow

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Abstract

This paper reports on the progresses obtained through the analysis of thermomagnetic features of the region between the southern part of Tocantins state and the northern part of Goias state, in Central Brazil. For that, we made use of data collected through aeromagnetic surveys. Techniques of shading applied to vertical derivative of Anomaly Magnetic Field (AMF) have been used to identify magnetic lineaments. The depth estimates of these structures were obtained by means of spectral Analysis of AMF (Centroid method). The results reveal the existence of a set of near-linear magnetic features in the region between the longitudes of 48^0W and 51^0W and between the latitudes of 12^0S and 14^0S. This is also an area of moderate microseismic activity and recent studies indicate anomalous geothermal conditions at the upper crust. However, direct evidences of the occurrence of magmatic intrusions at shallow crustal levels are absent. We postulate the hypothesis that the features identified as a result of aeromagnetic survey are indicative of fracture systems, thereby enabling the flow of carbonic fluids observed at the region's thermal springs and transporting geothermal heat.

1 Introduction

The heat present in crust layers is a natural geothermal energy resource whose practical exploitation is becoming increasingly widespread, worldwide. Geothermal resources are seen as an alternative source of clean and removable energy (Ozgener et al., 2007). Currently, the use of this source of energy is economically viable only in sites with an accumulation of geothermal fluids. Moreover, in the deepest crust, the great part of this geothermal energy is trapped in solid rock matrices.

In this context, the extensive crustal segments have become attractive targets for exploitation of resources from hot and dry rocks or hot and humid rocks types (Potter et al., 1974). There is evidence of geothermal sources and heat anomaly map by heat flow distribution in Trans-Brazilian lineament (TBL) region (Schobbenhaus, 1975). The geothermal activity evidences the potential to be used directly as thermal springs or even indirectly as the generation of electricity.

Aeromagnetic surveys have been employed in several studies of geologic provinces in central Brazil. The focus of most of these investigations has been the mineral and hydrocarbon exploitation at shallow depths, in the upper crust. Very few attempts have been made in using aeromagnetic data to explore crustal structures at deeper levels. (S. Guimarães et al., 2014) employed spectral analysis techniques of aeromagnetic data in the understanding of vertical distribution of magnetization in deeper crustal layers. This approach has recently been used in the study of magnetized crustal blocks in the adjacent cratonic region by (S. N. P. Guimarães & Hamza, 2019).

Geothermal resources of deep origin are generally related to magmatic intrusions (Kolstad & McGetchin, 1978) positioned at varying levels of the crust. As a result, studies of the crust's thermal field may be related to magnetometric investigations. In the present work, we examine the vertical derivative of the anomaly magnetic field (AMF) by using shading techniques (Blakely, 1996) in order to identify the magnetic lineaments in the study area involving important geothermal environment, such as thermal springs. The depths of these magnetic sources were inferred by spectral analysis of AMF.

The area under study is located in midwest region of Brazil cuted by the TBL, between 48^0 W and 51^0 W (longitude) and between of 12^0 S and 14^0 S (latitude).

2 Characterization of the Study Aea

The area of study comprise a parallelogram that includes the northern of Goiás state and southern of Tocantins state, in central Brazil, Figure 1.

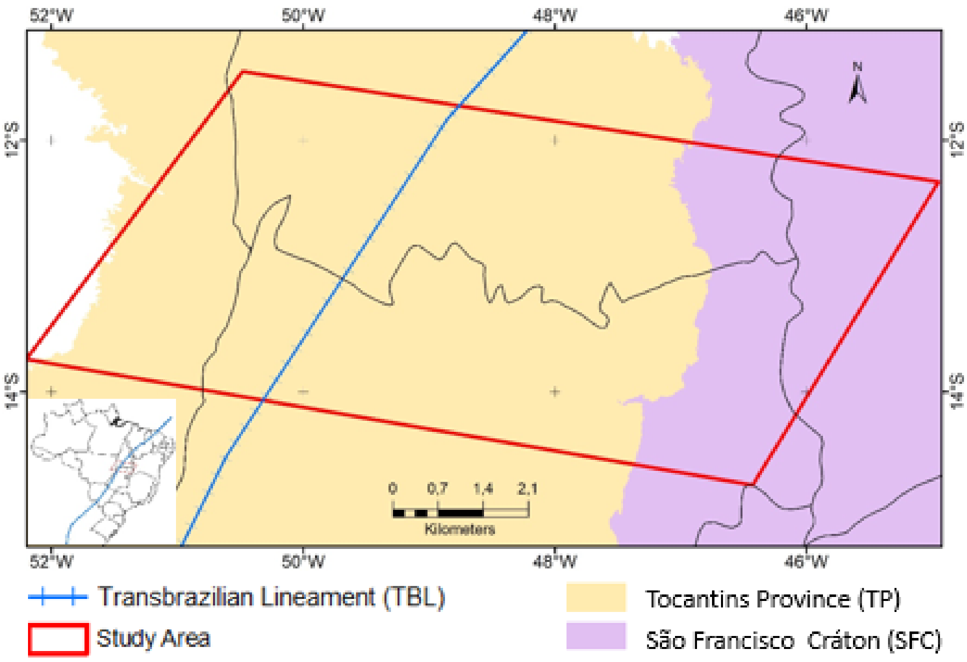

Figure 1: Location of study area.

The region lies on belts of phanerozoic covers (especially Brasília and Araguaia belts) which feature geothermal anomalies, as observed in heat flow map of Brazil (Vieira, 2015). The west part of this area is formed by the inner zone of Araguaia belt, Estrondo group and the orthogneiss manifested as a result of the Brazilian Cycle. In the central part of the study area lies part of Goiás Magmatic Arc and Goiás Massif which constitute important structural sequences for this study. In the east part, the study area is limited by the Tocantins Province (TP), characterised by the orthogneiss and greenstone belts of the Brasília belt and by the São Francisco Craton (SFC), marked by the Bambuí group. The regional distribution of these geological units are illustrated in the simplified geologic map of Figure 2.

Hot dry rocks in subsurface provide the ideal conditions of energy exploitation, due to the extent of high fracturing degree at the crystalline basement. Pioneering studies of TBL were carried out by (Schobbenhaus, 1975) and (de Brito Neves & Cordani, 1991).The deep geothermal resources are generally related to magmatic intrusions positioned at varying levels of the crust (3 to 10km) (Kolstad & McGetchin, 1978).

3 Data Acquisition and Methods

The aeromagnetic data used in this work is based on data sets compiled under the projects designated as Brazil-Canada Geophysical (PGBC), Magmatic Arc Mara Rosa (MAMR - Area 2), Paleo-Neoproterozoic of Northeast from Goiás (PNNG - Area 5), Tocantins (TO), Complement of Tocantins (CTO) and Rio Formoso (RF). These are public domain data sets, made available by CPRM for academic research purposes are illustrated in the Figure 3.

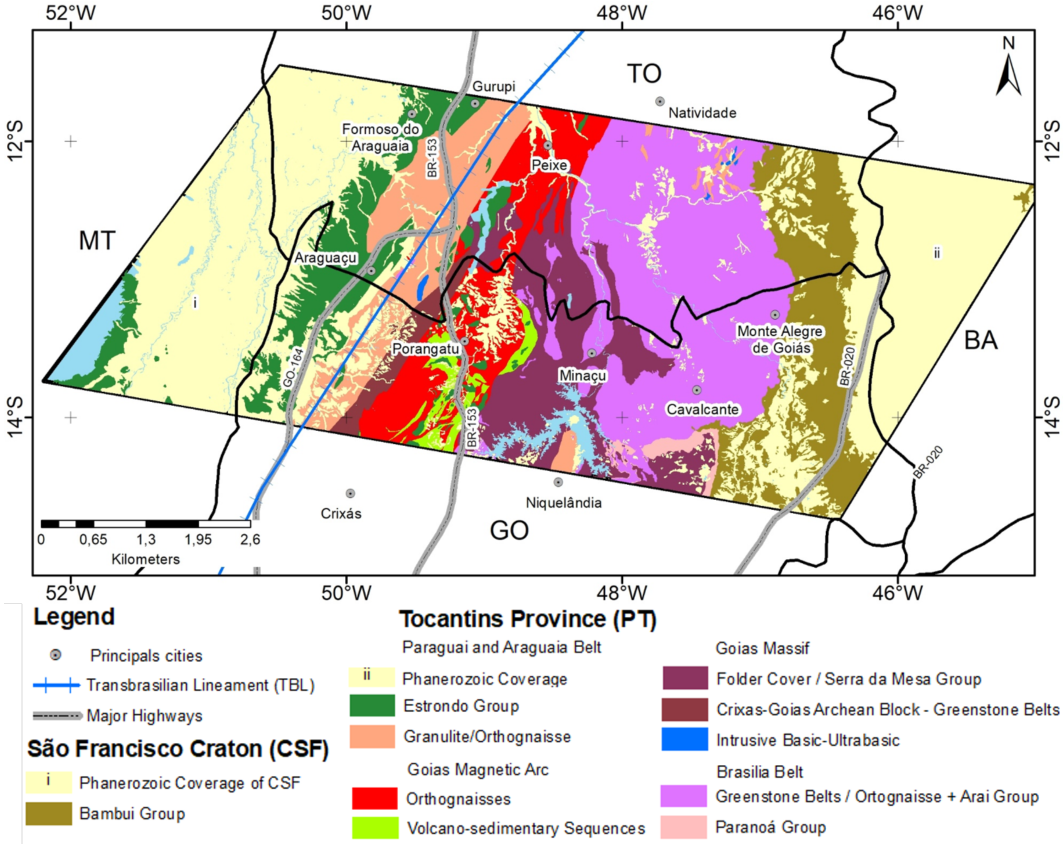

Figure 2: Simplified Geology Map pf the study area (Modified from (CPRM, 2014))

The main characteristics of used data sets are described in Table 1.

Different types of processing techniques were applied on both types of database. For PGBC data, corrections were made for levelling, micro-levelling and filtering. These were followed by the removal of geomagnetic field components (diurnal and principal - IGRF), which allowed derivation of the residual or anomalous field. For data collected after the year 2000, the AMF was acquired with all corrections and levelling applied. Then, suture techniques were employed to generate a unified dataset. The degree of coherence this union was verified by the application of directional filters. The AMF map is illustred in Figure 4, the parallelogram is a segment selected for the analysis of lineaments is also indicated, the blank areas on the polygon study indicating regions that have not been contemplated by the datasets.

3.1 Vertical Derivative of Crustal Magnetic Field

This is a processing technique for enhancing the high frequency of the magnetic signal where the magnetic anomaly is linearly transformed by means of the first derivative of the vertical component (z) of the AMF ($\vec{B}$), i.e., the vertical derivative measures the variation of the AMF with the vertical distance of source (Blakely, 1996).

In Fourier domain, it is defined by:

$$\Im\left(\frac{\delta^n B}{\delta z^n}\right) = |k|^n \, \Im\left[B\right] \tag{1}$$

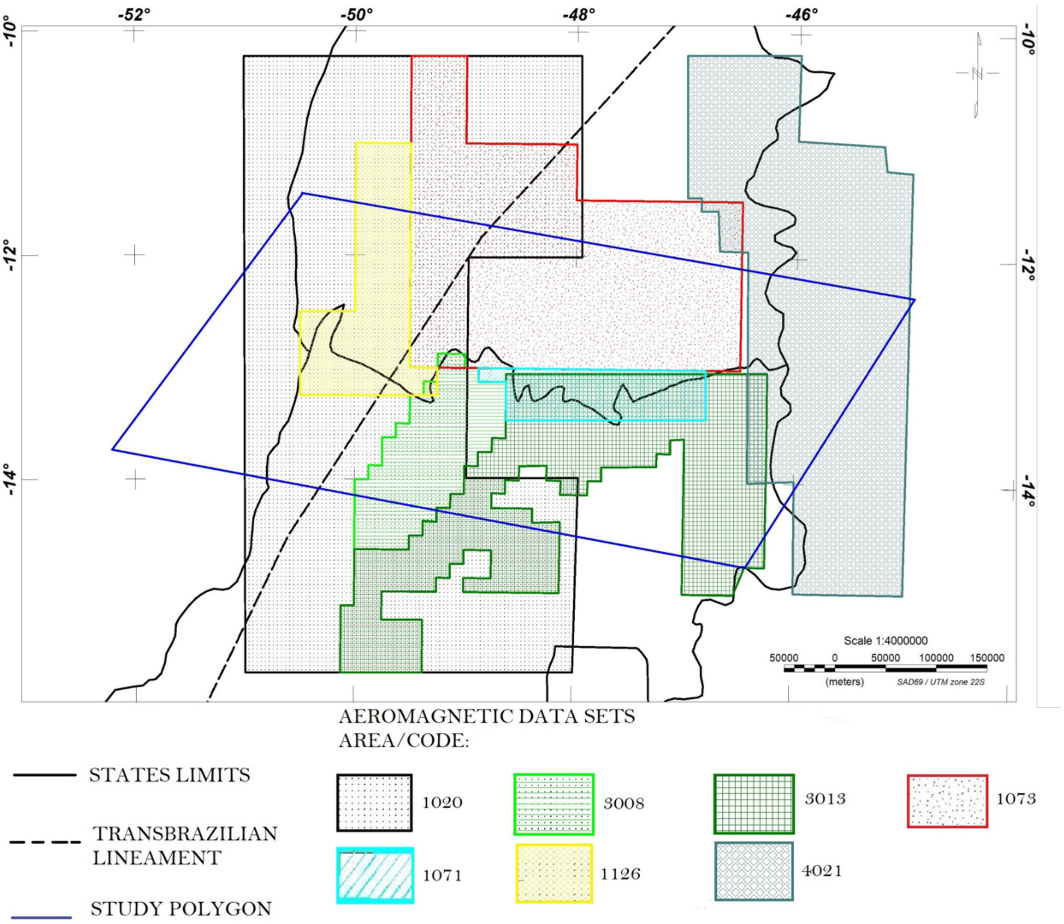

Figure 3: Areas of aerogeophysical projects used in this work.

$$k = \sqrt{(k_x)^2 + (k_y)^2} \tag{2}$$

The vertical derivative map enables a more detailed visualisation of the magnetic contrast identified by the AMF, thereby allowing a better observation of the fault system and tectonic events. It is physically equivalent to the measurements of the magnetic field at two very close points, and the calculation is worked out by the quotient between the subtraction of these two points of magnetic field by their vertical separation. When applied to the magnetic data of the AMF, the drivatives highlight the magnetic response of the more shallow geological bodies such as lineaments to the detriment of the deeper ones. Such a technique also assists the separation of anomaly Curves which may have been laterally superimposed.

In most cases, the features resulting from the application of this method appear as 'ridges', whose geographical distribution occurs along lines, thus constituting so-called magnetic lineaments. The mechanisms responsible for the connectivity of the magnetic lineaments are believed to be alterations in the magnetic properties and also brittle behaviour of geological formations resulting from the action of local tectonic forces (Costa et al., 1985) (Osako et al., 1999). In the former, changes in the direction of lineaments represent changes in lithotypes. In the latter, the locations of changes in the direction of lineaments represent the local fracture zones. In the present investigation, vertical derivative techniques were applied by using Geosoft Oasis Montaj package (2019).

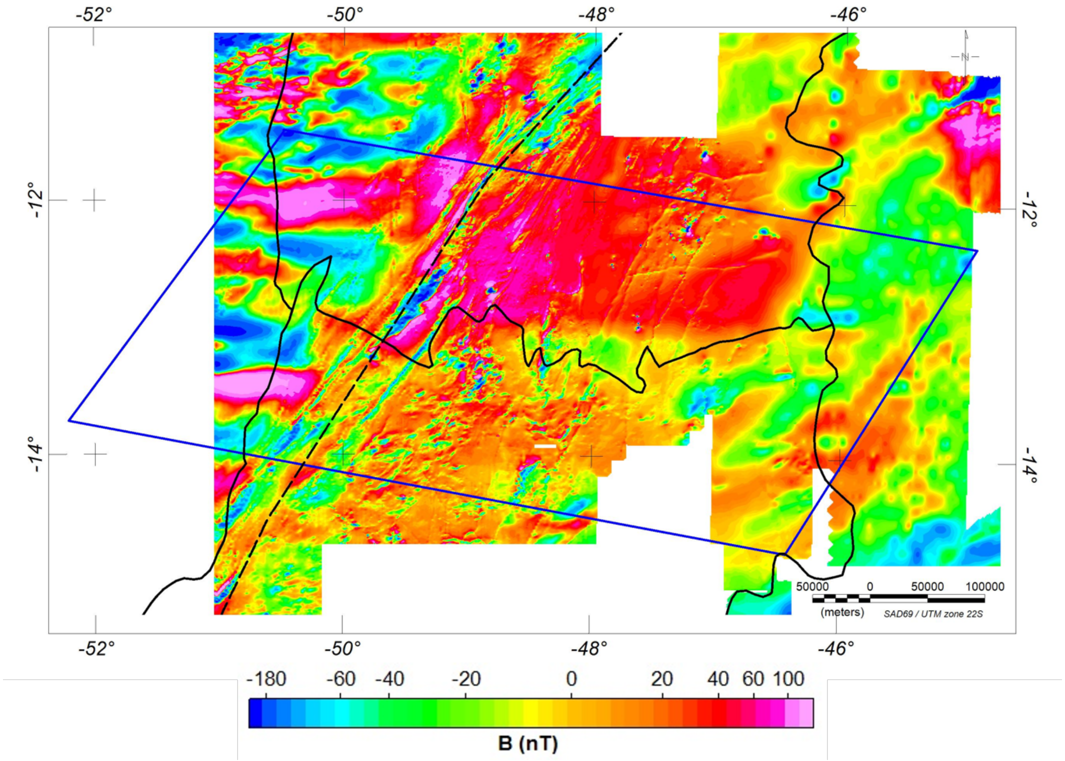

Figure 4: Crustal Magnetic Field Map in the study area.

3.2 Spectral Analysis of Crustal Magnetic Field

In order to determine the depth of magnetic sources in the subsurface, the spectral analysis technique used was the Centroid method (Bhattacharyya & Leu, 1977; Tanaka et al., 1999; Okubo et al., 1985). This method was initially based on the spectral tilt method proposed initially by (Spector & Grant, 1970). Both methods are based on the assumption that the anomalies observed in the AMF are produced by a distributed set of prismatic bodies. Assuming that these sets of magnetic sources form a semi-infinite layer and that their magnetization is a constant value, the Spector and Grant equation (1970) under the Blakely notation (1995), can be simplified as:

$$|F\,(k)|^2 = 4\pi^2 C_m^2\,|\theta_m|^2\,M_0^2 e^{-2kz_t} * \left(1 - e^{-k(z_b - z_t)}\right)^2 S^2\,(a,b) \tag{3}$$

where k is the wavenumber (cycles/km), C_m a constant, θ_m an angle related to the magnetization direction and θ_f an angle related to principal magnetic field direction in the final phase of acquisition data. M_0 is the magnitude of the magnetization vector, z_t and z_b are the top and bottom depths of magnetic sources. $S^2(a,b)$ is a factor related to horizontal dimensions of the anomalous magnetic source.

Therefore, the slope of the adjusted lines over the logarithm of the azimuth average power spectrum generated by a set of anomalous magnetic sources is related to the depth of the top of this set and also these spectra can relate a peak frequency (or wave number) to the thickness of the original magnetic layer.

In the Centroid method, the model is centred on collections of random samples of a uniformed distribution of prisms with constant magnetization. Thus, equation 3 is adjusted in terms that involve z_t and z_b in a hyperbolic sine function, plus a centroid factor and for long wavelengths, the hyperbolic sine function tends to one, leaving only the centroid term, thus:

$$|F(k)|^2 \sim Ce^{-kz_0}\Delta zk \tag{4}$$

In the methods proposed by (Bhattacharyya & Leu, 1977) and (Okubo et al., 1985), the estimates of the depth of the centroid (z_0) are obtained from the slopes of azimuthally averaged and the wavenumber scaled Fourier spectra in the low wavenumber region following the relation:

$$G(k) = \frac{1}{k}F(k) \tag{5}$$

Once the depth of the top of the deepest layer (z_t) is estimated from the amplitude spectrum, it is fairly simple to use the scaled amplitude spectrum to estimate the centroid depth (z_0). The bottom depth (z_b) is then obtained using the equation 6:

$$z_b = 2z_0 - z_t \tag{6}$$

The spectral analysis programme (routine in MATLAB) utilized enables changes in size of search windows, allowing calculation of the depth of magnetic sources in different parts of the study area.

4 Results and Discussion

4.1 Analysis of Vertical Derivative

The study of magnetic expressions of tectonic lineaments takes the enhancement of short wavelength anomalies. This is, on the whole, achieved by examining vertical derivatives of the AMF. Whence, maps of vertical derivatives are often employed in outlining tectonic lineaments. Magnetic imprints of lineaments arise from emplacement of thin sheets of material of relatively higher magnetic susceptibility. Fracture systems triggered by tectonic processes are responsible for the formation of a system of parallel fractures.

The study area involves two large-scale tectonic provinces: Tocantins Province (TP) that encloses the Trans-Brazilian lineament (TBL) on the western side and São Francisco Craton (SFC) on the eastern side. Analysis of the vertical derivative of the FMA indicated the presence of magnetic lineaments associated with TBL. These are closely-spaced linear magnetic features, as illustrated in Figure 5.

The cyan line in the map (Figure 5) is the lineament identified in previous geologic studies known as TBL. The magnetic lineaments were identified by adjusting lines connecting the darkest ridges on the vertical derivative Map. In the case, the red lines represent the near-linear features that have been considered as indicative of fracture zones in the basement rocks.

The greatest part of the magnetic lineaments, identified in subsurface by means of vertical derivative analysis, are around TBL, which shows that actually the TBL is a zone of lineaments with the same direction and characteristic of tectonics. It is evident from application of processing techniques that the dataset used in this study does not have a uniform resolution degree. In the vertical derivative this fact becomes patent in the SFC region and in the northwest region of study area. Hence, some lineaments were identified by cross-checking these with geologic information in order to increase the reliability in the data

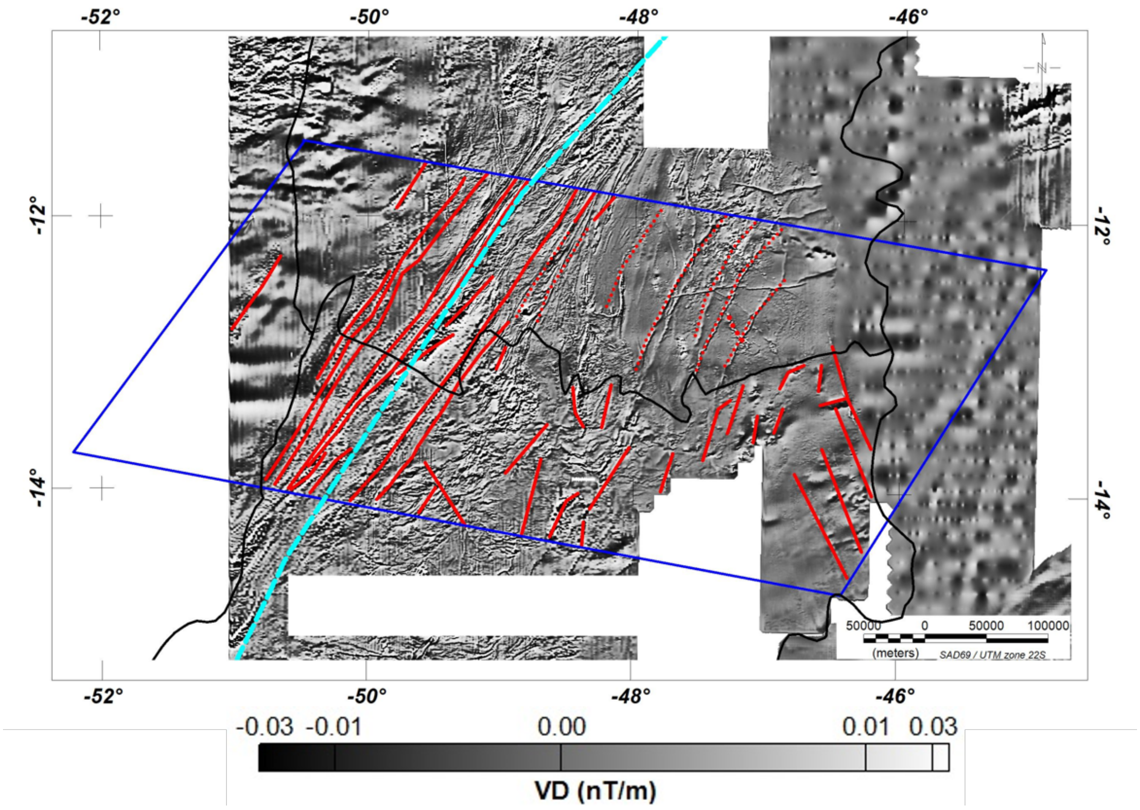

Figure 5: Distribution of Vertical Derivative of the Residual Magnetic Field in the study area. The red lines refer to mapping Magnetic Lineaments.

analysis. These lineaments are indicated in the map of Figure 5 as red-dotted lines. The blank segments in this map represent the areas deprived of the needed spectral resolution.

More than ten fracture zones with magnetic expressive ness can easily be identified in the vertical derivative map. These feature a NE-SW trending direction. Note that the lateral spacing (Figure 6), of such features is relatively small, ranging between 5 and 20 km, around TBL. The presence of such closely-spaced anomalies may be considered an indication that TBL in the study area is composed of a set of parallel quasi-linear fracture zones. Fracture zones are also observed in the region between TBL and SFC. Nonetheless, their spacing is relatively larger, of the order of tens of kilometres. The directions of these fracture zones are likewise NE-SW oriented, albeit in the north region a small change in the lineaments can be perceived to the E, 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 have been deemed as indications of fundamental differences 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 may indicate that the cratonic area may be comprised of relatively unbroken structural elements with practically no significant contrast in their magnetic properties.

4.2 Deep Crustal Structure

The spectral analysis of the FMA obtained from aeromagnetic data was used as a means to infer depth values of subsurface anomalous magnetic sources, thus investigating

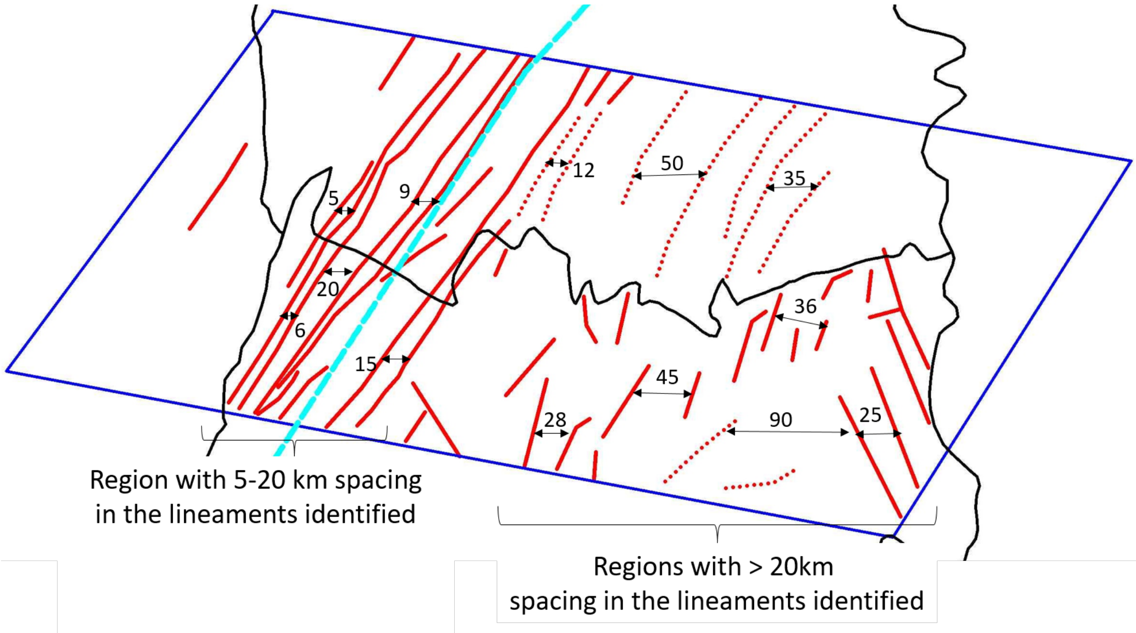

Figure 6: Fractures Spacing identified using Vertical Derivative techniques.

some fundamental points of the crust's thermal history in the given study area. As a consequence of data availability, three sizes of investigation window were employed, these being: 150km, 225km and 300km. The centroid method used in this study allows the identification of magnetized layers as per their wavenumber range, and consequently, three types of sources can be recognised: shallow, intermediate and deep. The results obtained through this method are presented in Table 2.

With the depth values for the magnetic layers acquired in the study area, the estimated value for Curie surface varies between 42 and 55km, with the shallow source layer limited to a 2-km depth. Figure 7 illustrates this subsurface arrangement of the magnetized crust or Curie surface.

Deep crustal structures of the study area may be assumed by considering vertical variations in Moho depths, Curie temperatures and heat flow along selected profiles. The first profile (P1) has NE-SW direction, between the longitudes 50^0W and 48^0W and coincides with the TBL direction. It is situated in the western part of the study area. The second profile (P2) have a W-E direction cutting across the structural provinces of TP and SFC. The third profile (P3) have NE-SW direction, between the longitudes 47^0W and 46^0W and it is within the SFC. Values of Moho depths along the profiles are based on results reported by seismic studies of the region (Assumpção et al., 2013). Variations of Moho and Curie depths along the P2 are shown in Figure 8.

In this Figure 8, the top panel indicates variations in Moho and Curie depths, while the bottom panel illustrates heat flow variations (magenta curve). It is evident that there is a prominent heat flow anomaly in the region between TBL in TP and SFC. The variations of the Moho and Curie depths in the two others profiles listed above (P1 and P3) are illustrated in Figure 9 and Figure 10, respectively.

The P1 coincides with the TBL region mapped by (Schobbenhaus, 1975). In this profile region, the variations in Moho and Curie depths are much subdued. The heat flow in this region varies around 80mW/m^2, which is considered high for Brazilian heat flow standards in view of its geological structure and rock age. In fact, in this region geothermal sources

Table 1: Main Characteristics of Airborne Geophysical Datasets used in this study.

	PGBC	MAMR	PNNG	TO	CTO	RF	SF
Code	1020	3008	3013	1073	1071	1126	4021
Acquisition Year	1976	2004	2006	2006	2007	2014	1980
Geophysical Information	Mag/ Gamma	Mag/ Gamma	Mag/ Gamma	Mag/ Gamma	Mag/ Gamma	Mag/ Gamma	Mag/ Gamma
Line Spacing	2 Km	500 m	500 m	500 m	500 m	500 m	500 m
Tie Spacing	14 Km	5 Km	5 Km	10 Km	10 Km	10 Km	12 Km
Line Direction	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 Height	150 m	100 m	100 m	100 m	100 m	100 m	125 m
Range of Samples (mag/gamma)	1s	0.1/ 1.0s	0.1/ 1.0s	0.1/ 1.0s	0.1/ 1.0s	0.1/ 1.0s	0.1s

Table 2: Depth from top to bottom of Magnetic sources obtained in Spectral Analysis by Centroid Method, by investigation window size in the study area.

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

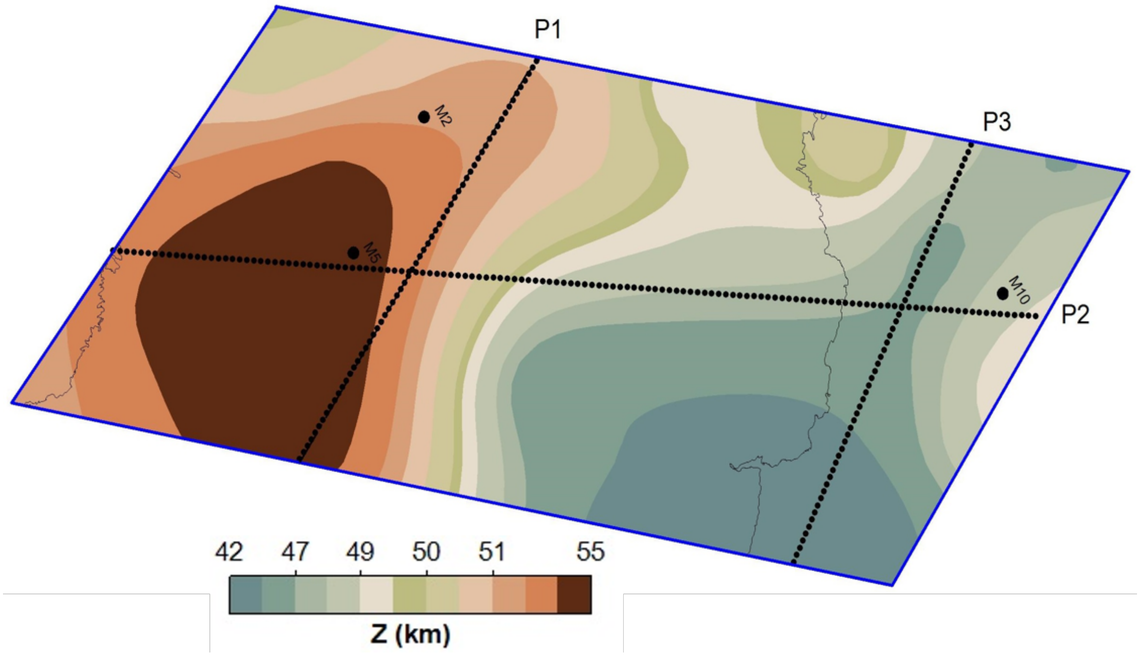

Figure 7: Depth of Magnetised Crust or Curie Surface using the deepest layers values from the Spectral Analysis. The dotted lines indicate the profiles selected for detail investigation.

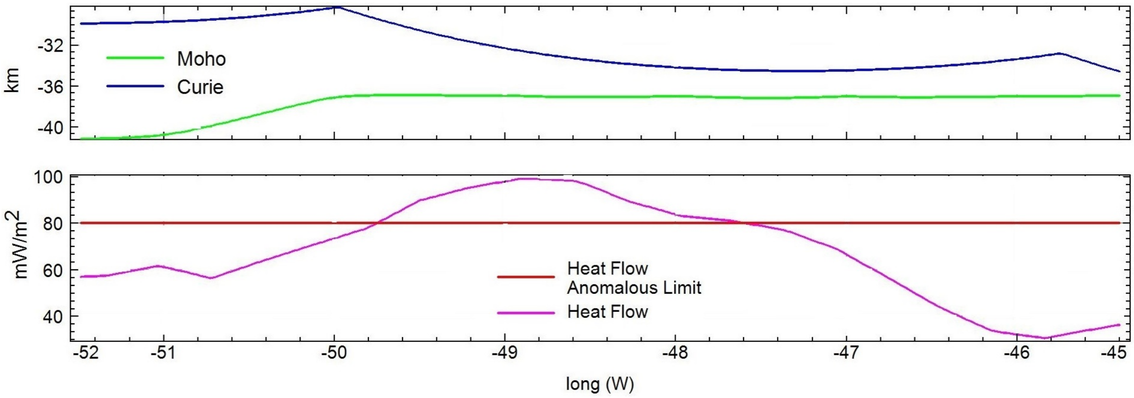

Figure 8: Lateral Variations in the Curie surface, Moho depth and Heat Flow along the Profile (P2) in the Central region, West-East (WE) direction of the study area.

that can be associated with the basement of the Paraguay belt and the magmatism of Goiás Magmatic Arc. The P3 is located at the SFC. The rocks that make up this area basement are very ancient and as a consequence, all the accumulated heat in the rock formation dissipated and the region is now considered geothermally cold. The values for heat flow in this profile are not greater than 50mW/m^2. Additionally, it is evident that heat flow variations are much less subdued along the northern (P1) and southern (P3) parts of the study area. On one hand, both profiles (P1 and P2) bear the same crust depth comportment, where the Moho limits the magnetized crust (Curie surface), without evidencing any crust tuning. On the other hand, we can observe the outcrop geothermal sources in this region that demonstrate geothermal anomalies associated with tectonics and structural contexts.

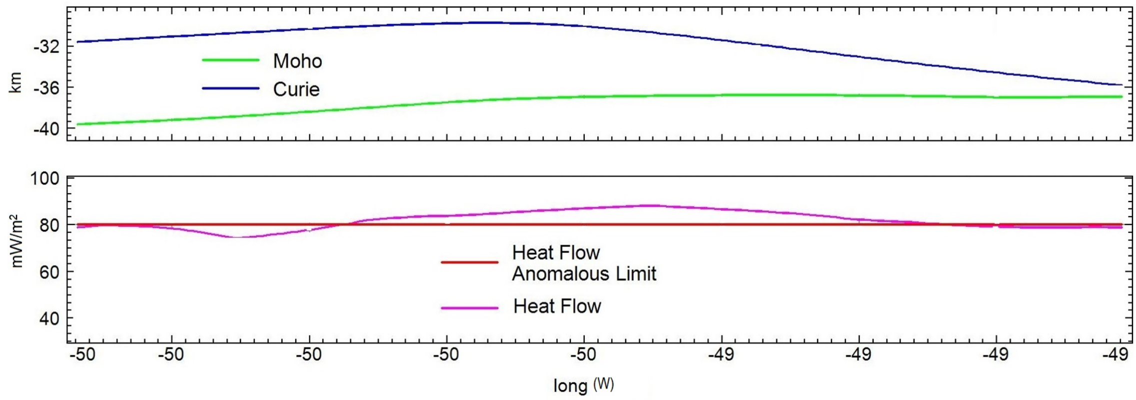

Figure 9: Lateral Variations in the Curie surface, Moho depth and Heat Flow along the Profile (P1) in the region of TBL, North-South (NS) direction of the study area.

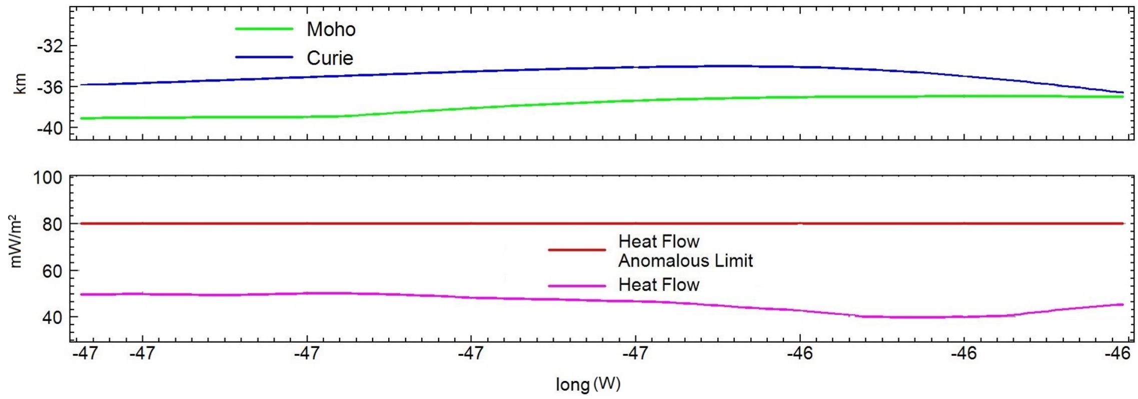

Figure 10: – Lateral Variations in the Curie surface, Moho depth and Heat Flow along the Profile (P3) in the region of SFC, North-South (NS) direction of the study area.

4.3 Spacing between Elements of the Lineament

Geologic lineaments are usually defined in literature as interpreted lines that have visible relations with geometrical features of terrain forms, such as valleys and slopes. A notable feature of the lineaments in Figure 4 is the high degree of parallelism between fracture zones. This is often taken as consequence of the thermomechanical nature of the rupture process in geological materials (Schultz & Fossen, 2008). The spacing between fracture zones can be measured in terms of the average distance between features in the lineament.

According to (Lamur, 2018) and (Lamur et al., 2017) changes in fracture spacing are produced by the upflow of hot material. In case of rapid upflow of high temperature molten magmatic material, the failure of confining rock strata takes place on a relatively short-time scale. The resulting fracture zone is an elongated feature with parallel sidewalls. Ergo, pulses of magma eruptions bring about sets of closely-spaced fracture zones. Similarly, in case of weaker effusive eruptions, internal pressure builds up on relatively longer time scales, producing fractures with larger Spacing. In brief, fracture spacing may indicate the type of fluid flows during the occurrence of lineaments. In this sense, effusive eruptions imply transport of geothermal heat by an upwelling flow of fluids rich in water or carbon dioxide (CO_2).

Hence, areas with wider fracture spacing are likely to be associated with localised heat flow anomalies.In the region of TP (involving TBL) the spacing of fracture zones is less than 10km wide and several hundreds of kilometres long. These fracture zones feature a NE–SW trending direction. Contrastingly, in the region between TP and SFC the lateral spacing of fractures are relatively larger, ranging between 10km to 50 km.

4.4 Geothermal Field of the region between TBL and SFC

A recent geothermal study conducted by (Descovi & Vieira, 2019) has identified an anomalous geothermal field in the region between TBL and SFC. In this area, geothermal gradients vary from $15-55^0$C/km while thermal conductivity values are in the range between 2.2-3.2 W/m.K. Consequently, heat flow values range from 40-160 mW/m^2. The heat flow map derived from the results obtained in the present work are illustrated in Figure 11. Therefrom, it can be inferred that heat flows in the region between TBL and SFC reach values in excess of 80 mW/m^2, in contrast to SFC, which has the lowest values of heat flow, to a great extent, smaller than 50 mW/m^2.

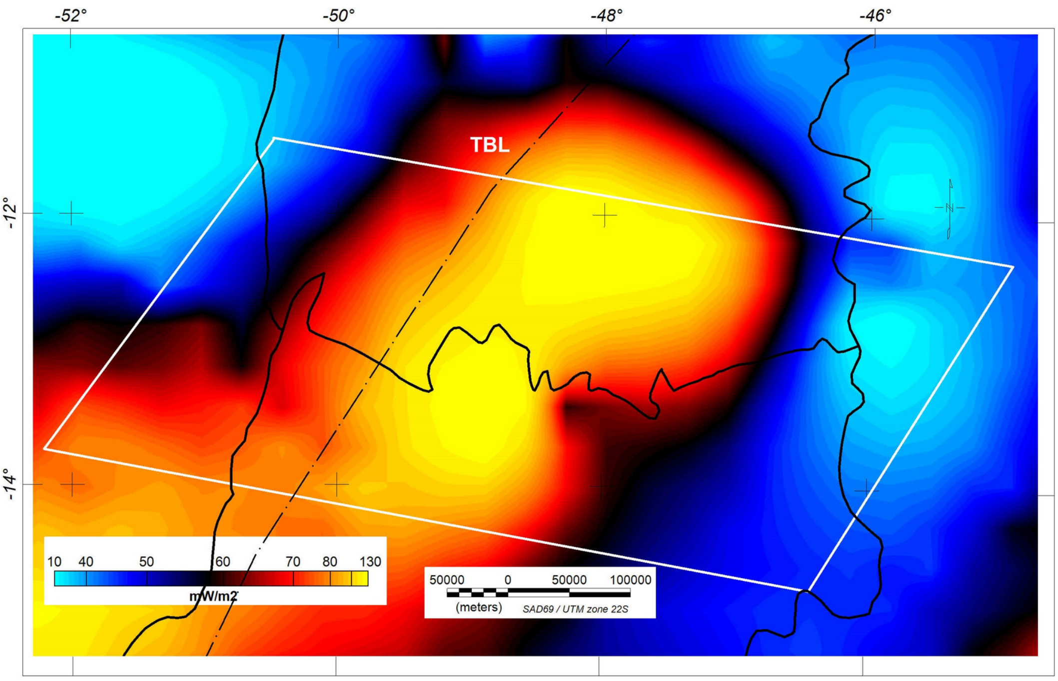

Figure 11: Heat Flow map of Northern Goiás and Southern Tocantins region between PT (involving TBL) and CSF.

It is clear that the anomalous geothermal conditions prevail in the region between TP and SFC in the northern parts of the Goiás state and southern parts of the Tocantins state. However, direct evidences of occurrence of magmatic intrusions at shallow crustal levels are absent. The great geothermal anomaly in this region can then be explained by the supplementary heat transport resulting from the ascending flow of carbonic fluids (Descovi & Vieira, 2019; Pinto-Coelho & Moura, 2016; Padilha et al., 2013; Abdallah, 2016; Solon et al., 2018) through the BR-19 quaternary fault (Porangatu fault zone).

5 Conclusions

Shading techniques applied to vertical derivative and spectral analysis of FMA have been used to identify and typify magnetic lineaments. The results obtained reveal the existence of a set of near-linear magnetic features in the region between 48^0W and 51^0W of longitude and between of 12^0S and 14^{0o}S of latitude. Along the western side of the study area, the spacing of magnetic lineaments ranges between 5km to 10 km. Contrastingly, along the eastern segment of the study area, the spacing of fracture zones ranges from 10km to 50 km. This difference in the spacing of fracture zones has been considered an indicative of changes in the nature of deep-seated tectonic processes.

The magnetic sources depth inferred from the spectral analysis technique in the region spans from 35km to 50km. In the most part of the TP (involving TBL) region the thickness between the Curie and Moho surfaces differ in 10km. In the SFC region, this difference becomes almost null (2 km), evidencing that almost all the crust is magnetized.

The region between TP and SFC has moderate microseismic activity 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 present work, we suggest the possibility that features identified in aeromagnetic datasets are indicative of fracture systems which made up-flows of carbonic fluids viable thereby transporting geothermal heat. The presence of flows of CO_2 has been observed at sites of thermal springs in the region.

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