Interpretation of Magnetic Anomalies of the Caiabis Basin, Southwestern Amazonian Craton, Brazil

Adolfo Barbosa da Silva (CPRM-GO), Rafael Ribeiro Severino (CPRM-SP) and Gabriel de Freitas Gonçalves (CPRM-GO)

This paper was prepared for presentation during the 16^{th} International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 19 - 22 August, 2019.

Abstract

In this expanded abstract, we have studied the airborne magnetic data on the Caiabis Basin, Mato Grosso State, Brazil. Using processing techniques like regional-residual separation by spectral analysis, anomaly centralization by vertical integration and estimative of magnetic source depth by Werner Deconvolution, we have proposed that the magnetic anomalies from Caiabis Basin may be related to: basement; lineaments; manganese ore and; sediments/basement interface in the Porto dos Gauchos seismic zone. In this last case, we also verified that the magnetic source depth estimates provided by Werner solutions are agreement with other depth estimates given in seismic studies.

INTRODUCTION

The aeromagnetic data constitute an important information source at sedimentary basins studies. By means of these data it is possible to infer the depth and structure of the basement, identify intrusions and / or mafic units intrinsic and even magnetic features related to mineralization (GUNN, 1997).

There is a vast bibliography about researches that utilized airborne magnetometric data interpretation at Brazilian sedimentary basins studies, mainly in relation to paleozoic and continental margin basins. For the most part, these studies aimed to understand the tectonosedimentary evolution of these basins with a focus on the discovery of mineral resources. However, the use of airborne magnetometric data has been less applied in pre-Cambrian sedimentary basins studies from Amazonian Craton. An instance of this reality it has been the lack of geophysical studies on Caiabis Basin.

The Caiabis Basin (CB) has a rhombohedral shape with $500\ km\ x\ 100\ km$ with an elongament in NW - SE direction. The relief is flat, with topographic heights of less than $400\ m$ (FRASCA & BORGES, 2005). Due to the large extension of this basin, sparsely populated areas and the few paved roads, the logistics for a field work ends up becoming technically difficult and financially onerous. This results in a few points of described outcrops and, consequently, creates a gap in the evolutionary understanding of the basin and it potential to contain mineral resources. In this scenario, airborne geophysical surveys are essential for mapping this region, because through them it is possible to acquire information about the properties of the lithological units that make up the CB, covering a large area with low financial costs.

Utilizing some processing technical applied on airborne magnetometric data acquired in recent years, the present work aimed to identify some magnetic anomalies at CB. Once identified such anomalies, we have interpreted in terms of geological information based on previous studies.

GEOLOGICAL SETTING

CB is located south from Amazonian Craton and north from Parecis Basin, middle-north region of Mato Grosso state, Brazil. It is layered over the igneous and metamorphic, crystalline basement, rocks of the Juruena Terrain and composed by the Caiabis group, which can be divided in two units: the sedimentary successions of Dardanelos Formation; and mafic intrusions of Arinos Formation (Figure 1).

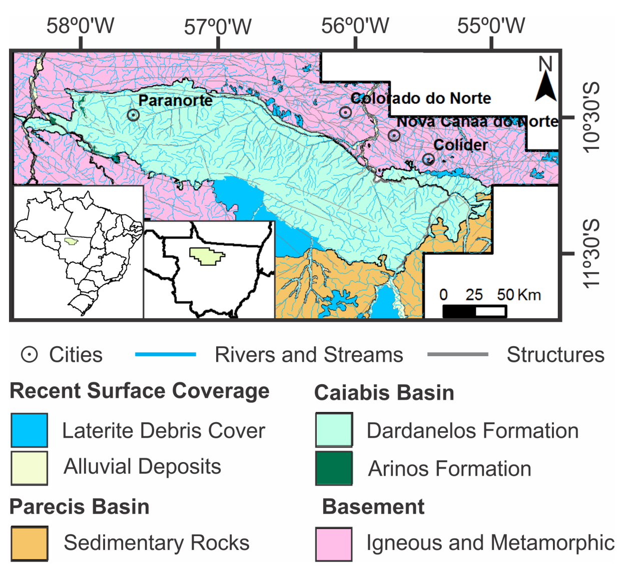

Figure 1: Geological map from Caiabis Basin (CB).

The sedimentary sequence was divided in many different units, by FRASCA & BORGES (2005) and, mainly, by SOUZA & ABREU FILHO (2007). In general, the sedimentary successions are composed by conglomerates and conglomeratic sandstones at the base with normal gradation for thick, medium and fine quartz sandstones at the top. It has trough cross stratifications and finer facies variations with parallel bedding. Is interpreted, essentially, as a fluvial depositional environment, transitioning to a transgressive deltaic system. LEITE & SAES (2003), through Pb/Pb dating in detrital zircons of the basal conglomerate, generated ages between 1.98 and $1.37\ Ga$ and thus suggested a maximum sedimentation age of $1.44\ Ga$.

The Arinos Formation is represented by basalts, diabase, olivine and gabbros which occurs mainly in form of sills, interleaved with sandstones of the Dardanelos Formation, aged 1.4 and $1.2\ Ga$ obtained by K/Ar method (SILVA, 1980).

Tectonically, CB has different interpretations regarding its type and mechanism of formation. ULHEIN *et al.* (2015) and LEITE & SAES (2003) suggest a rift basin of mesoproterozoic age. FRASCA & BORGES (2005) interpreted as sinister transcurrent zones with N70-80W directions that result in a pull-apart system. Although there is a lack of studies in relation to the tectonic forming this basin, it is possible to infer that it is an extensional or transcurrent environment generated in the Mesoproterozoic with reactivations of brittle structures.

METHODOLOGY

The airborne geophysical data utilized this work are from Juruena River, Serra dos Caiabis and Northern Mato Grosso States Aerogeophysical Projects. The data were acquired between 2013 and 2014 years and all them belongs to CPRM. The flight and ties lines spacing were $500\ m$ in N - S direction and $10\ km$ in E - W direction. The average terrain clearance height was $100\ m$. Using the software Oasis Montaj® (Version 8.5) of the GEOSOFT^{TM}, the airborne magnetometric data from the three projects were interpolated by the bidirectional method with cell size of $125\ m$, so that we obtained three grids separated. Subsequently, these grids were integrated by the suture method (JOHNSON *et al.*, 1999) in order to obtain only one grid.

After the data were joined, the map of the Anomalous Magnetic Field (AMF) from CB area was obtained (Figure 2). In a first analysis on AMF, it was possible to observe three regional magnetic anomalies (M1, M2 and M3) and a large number of minor linear anomalies, mainly in the southeast regions of M2 anomaly. In order to highlight these minor magnetic anomalies, a regional-residual separation was performed through analysis from Radial Power Spectrum (RPS).

From the application Fast Fourier Transform (FFT) on the AMF data, an analysis of the Radial Power Spectrum (RPS) was performed as a function of the wave number (SPECTOR & GRANT, 1970). In the ln(RPS) curve (Figure 3), three tangents straight lines were identified from which were identified three different magnetic sources ensemble. Table 1 shows the linear fit parameters $y = ax + b$ for theses straight lines, together with the respective R^2 coefficient, and the estimate of the mean depth h of the tops of the magnetic sources. The data clustered in sets 1, 2 and 3 were defined as being Deep, Intermediate and Shallow magnetics sources responses, respectively. The set 4 was considered to be essentially noise.

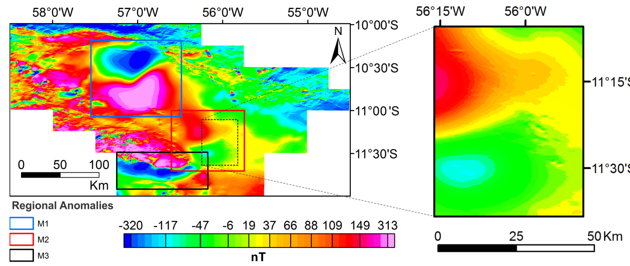

Figure 2: AMF map from CB area with the identified M1, M2 and M3 regional anomalies. The square in highlight shows the minor linear anomalies in the SE portion of M2 anomaly.

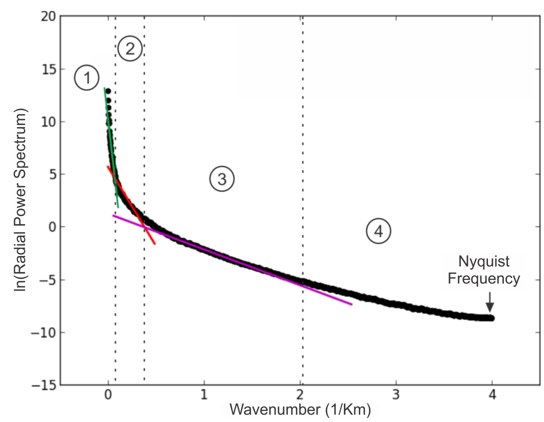

Figure 3: Radial Power Spectrum (RPS) from AMF data. The magnetic source ensemble identified by tangents straight lines are interpreted as being: 1 - Deep; 2 - Intermediaries; 3 - Shallow. The set 4 was considered as noise.

Based on the premise that regional magnetic anomalies have been related to the deep magnetic source ensemble, the wavenumber $n = 0.079$ ($\lambda = 12658.22m$) was taken as a representative of these anomalies. The separation of such anomalies from the original AMF was performed in five steps (Figure 4):

I Application of a low-pass filter (LP) on AMF in frequency domain using the wavelength considered as representative of the regional anomalies, generating the **LP-AMF** grid;

II Anomaly centralization by applying the Integral Vertical transform (IV) (PAINE *et al.*, 2001) on the grid generated at previous item, generating **IV- LP - AMF** grid;

III Application of the Analytical Signal Amplitude (ASA)

Table 1: Linear adjustment values and depth estimation.

Ensemble	a	b	R^2	h (Km)
1	-76.57	10.21	0.91	6.1
2	-14.98	5.67	0.93	1.2
3	-3.39	1.23	0.97	0.3

(NABIGHIAN, 1972; ROEST *et al.*, 1992) on **IV-LP-AMF**, thus generating the **ASA-IV-LP-AMF** grid so that this is in the same dimension as the original AMF;

IV Application of the IV on the AMF (**IV-AMF**) and, subsequently, it was applied the ASA on the **IV-AMF** generating the **ASA-IV-AMF** grid;

V Finally, the grid obtained in item IV has been subtracted from III, resulting in **RES-ASA-IV-LP-AMF** grid. This last grid will be referenced only as residual AMF.

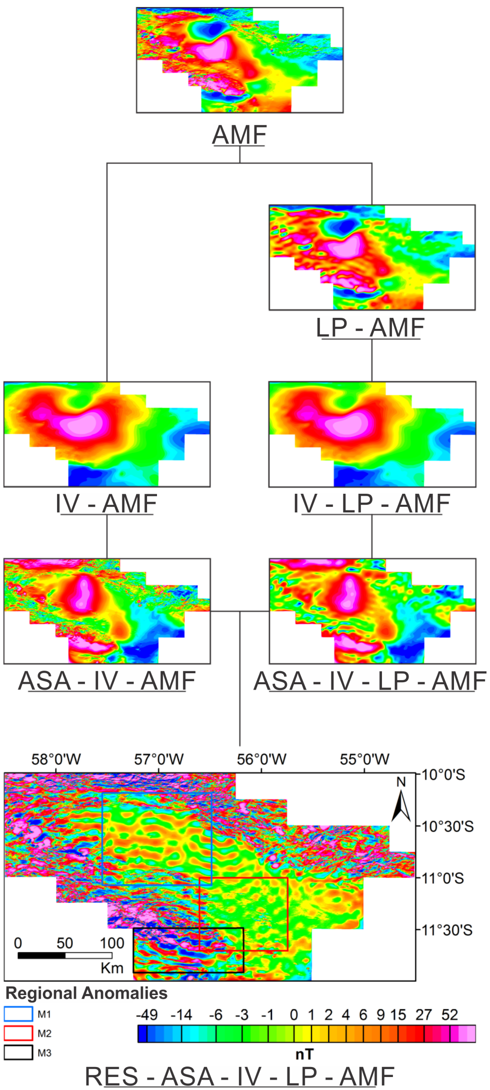

Figure 4: Processing flowchart utilized in the regional-residual separation.

After the residual AMF grid has been computed, this grid was sampling into the magnetic database (Serra dos Caiabis Aerogeophysical Projects) and then we applied the Werner Deconvolution (WERNER, 1953; KU *et al.*, 1983) for estimate the magnetic source depth. It has been considered only the Werner solutions close to seismic stations in the region of M3 anomaly. In this region, named Porto dos Gauchos Seismic Zone (PGSZ), BARROS & ASSUMPÇÃO (2011) estimated the sedimentary package depth based on receiver functions analysis and seismic refraction experiments. So, we have compared the depth estimates provided by magnetic (computed by this study) and seismic (computed by BARROS & ASSUMPÇÃO (2011)) data. The parameters used to Werner deconvolution are in Table 2 and the seismic station localization is in the Figure 5.

Table 2: Parameters values considered for calculation of the Werner solutions.

Field Strength	$23.993,58\ nT$
Declination	-16.5°
Inclination	-9.2°
Min. Length and Expansion Increment	$500\ m$
Max. Length and Shift Increment	$1000\ m$

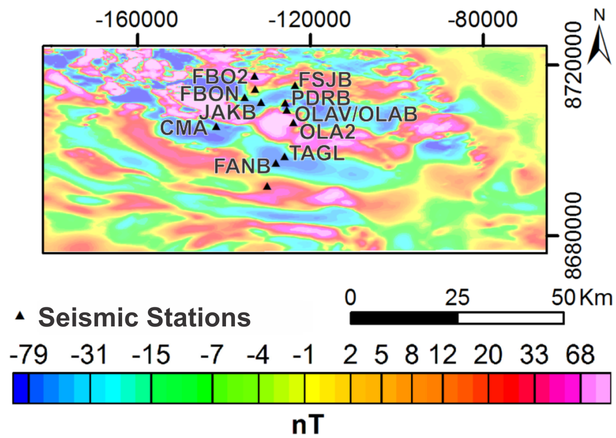

Figure 5: M3 anomaly location and the distribution of seismic stations used to monitor earthquakes. Note the magnetic anomalies with E-W direction.

RESULTS

In the Figure 4, we can see the influence of the regional anomalies was severely suppressed in the final residual grid, so that the minor anomalies in the CB southeast portion have become more evident.

The removal of M1 and M2 regional anomalies allowed the highlight of smaller linear anomalies. These smaller anomalies are large magnetic curvilinear lineaments that delimit the CB southeast edge and reach the NW portion of the basement (Figure 4). First Vertical Derivative (FVD) was applied on the residual AMF in the frequency domain to highlight the magnetic lineaments and to facility their extraction. In the region from M1 and M2 anomalies, the magnetic lineaments preferential directions are dominantly E-W. Nonetheless, it is possible to identify some magnetic lineaments with NE-SW and NW-SE preferred directions, the latter being more representative in the region of M2 anomaly. In this same region, the lineaments appear to reflect a large shear zone (Figure 6).

Also in M2 region, there are some anomalies set whose magnetic response appears to be more intense than the linear magnetic anomalies previously described. These anomalies intense is characterized by the facility to identify

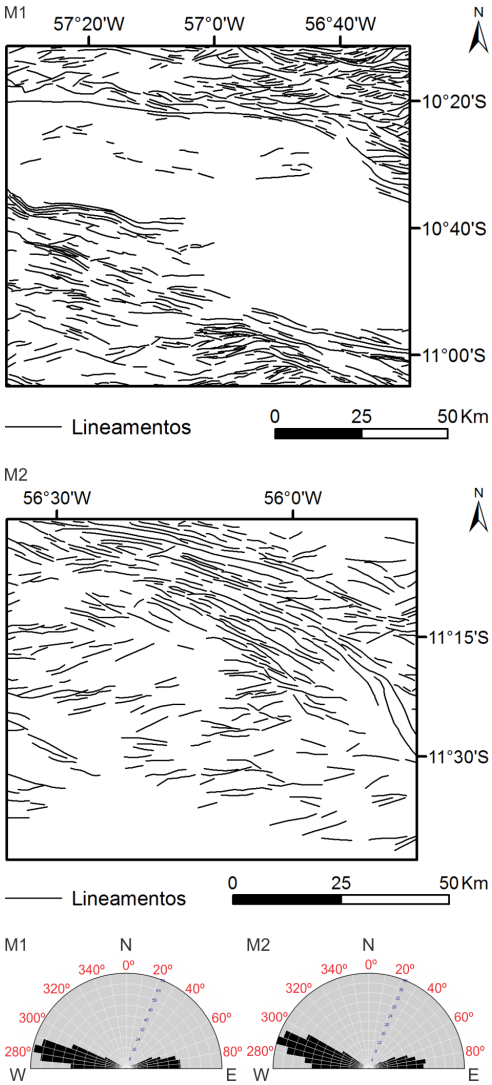

Figure 6: Magnetic lineaments drawn from the FVD on the residual AMF from M1 and M2 regions, together with the respective distributions of preferential directions.

their positive and negative lobes on residual AMF image and by the facility to distinguish such set on ASA residual AMF images (Figure 7).

According to a query made on the Mineral Production National Department (DNPM) site on 2017/11/22, some of these intense anomalies occur in areas that has been required for manganese ore mining by Ferlig Ferro Liga Company.

The residual - regional separation did not completely remove M3, thus showing that this anomaly has a magnetic field component related to the high frequencies. However, the technique allowed the discrimination between the sedimentary domain, located in south, and the domain of the basement, located in north. The former is characterized by a smoother magnetic signal pattern, while the latter is characterized by a more wrinkled pattern. In both domains, there are many magnetic linear anomalies with E-W preferential direction. For this region, the results also

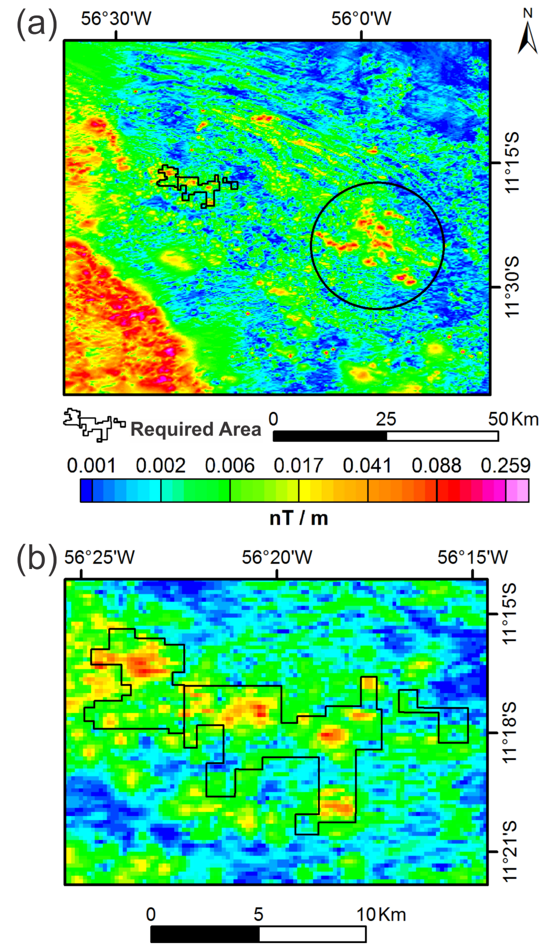

Figure 7: ASA residual AMF map showing details of occurrence region of M2 anomaly. In (a), we can see some regions with high magnetic signal in the CB and some them occur within the area required for mining Mn (b).

have revealed that the locations of the Werner solutions are very close to seismic stations, averaging $400\ m$ apart. The depths provided for both seismic and magnetic methods are similar, yielding $\sim\ 290\ m$ average depth for the former and $\sim\ 360\ m$ average depth for the last (Figure 8).

DISCUSSION AND CONCLUSION

There are few studies that specifically addressed the magnetic signatures from Caiabis Basin. However, there are several works in which it has been approached the geophysical signatures from Parecis Basin and some of structural aspects from Caiabis Basin, especially regarding the basement depth in its SE portion (BRAGA & SIQUEIRA (1995) *apud* BARROS & ASSUMPÇÃO, 2011; SANTOS & FLEXOR, 2012; SIQUEIRA, 1989; BAHIA *et al.*, 2007; FARIA, 2015). According to some of these studies, basement depth in the SE portion from CB is located between 4 and $8\ km$ (SANTOS & FLEXOR, 2012; BRAGA & SIQUEIRA, 1995) and may reach up to $10\ km$ of depth (FARIA, 2015). Since the M1 and M2 anomalies were completely removed by spectral analysis, we suggest that the magnetic signal from these anomalies may be included in the ensemble of magnetic sources with a mean depth

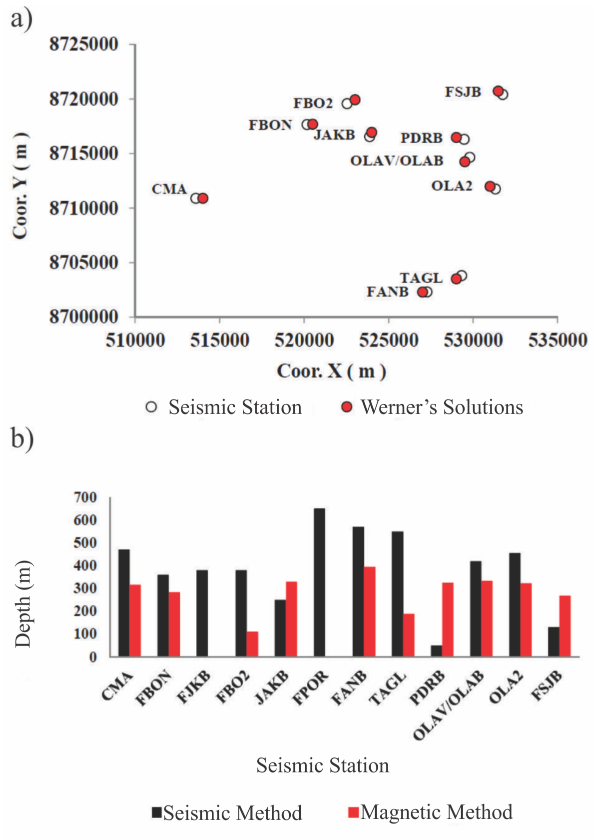

Figure 8: a) Comparison between the seismic stations locations and Werner Deconvolution solutions locations. b) Comparison between depth values obtained by the two geophysical methods.

of $\sim 6\ km$ (deep sources) and are related to basement structures. According to GUNN (1997), strongly magnetic anomalies with circular shape in sedimentary basins are strong indications of mafic intrusions. The reversed polarity from M1 evidence strong magnetic remanence, which leads us to conclude that the magnetic sources ensemble that originate it is rich in ferrimagnetic minerals and, therefore, constitute a strong indication for existence of a mafic intrusion in the basal basin portion. In the case of M2, there are at least two possibilities for its cause: its magnetic sources may have been generated by the same magmatic event that originated M1, but at different time intervals so that the magnetization direction were contrary to the M1 or; its magnetic sources would have the same magnetic properties as the sources that have generated M3.

The removal of M2 made it possible to identify long magnetics lineaments and some isolated magnetic anomalies in the southeastern basin portion, suggesting that the magnetic sources of these features are located at depths of $< 6\ km$. Observing the power spectrum results analysis, it is suggested that the magnetic sources causing these anomalies are included in the sets of intermediate magnetic sources ($1.2\ km$) and/or shallow sources ($0.27\ km$).

As mentioned earlier, some of these isolated anomalies in the Caiabis Basin SE portion coincide with the location of an area that has been request for manganese ore mining. Although there is a possibility that area is not effectively related to Mn mineralizations, it should be pointed out that jacobisite/maganomagnetite mineral whose chemical formula can be represented by $Fe_{3-x}Mn_xO_4$, may have ferromagnetic properties for $0 \leq x \leq 2.5$ (CLARK, 1997). In fact, RAO & BHIMASANKARAM (1961) pointed out magnetic responses observed in Mn mineralization zones could be due to varying manganomagnetite and vrendebugite proportions, the latter mineral being a Mn and Fe oxides variety with similar properties to jacobisite. The RAO & BHIMASANKARAM 's observations suggests the possibility for manganese ores existence in CB. Nonetheless, it is important to carry out new field studies that may identify the cause of these magnetic anomalies together with petrological studies that may identify the major magnetics minerals which may have generated airborne magnetic response observed in our studies.

The power spectrum analysis results shows that the M3 anomaly has long and short wavelength components, suggesting its magnetic source may be interpreted as a block (or set of blocks) with magnetic expression at various depth levels. In this interpretation line, magnetic source from the M3 anomaly may be related to Brasnorte Horst (BAHIA *et al.*, 2007; FARIA, 2015). This fact would agree with the basement depth estimates observed by BRAGA & SIQUEIRA (1996) as well as by BARROS & ASSUMPÇÃO (2011).

As explained by BARROS & ASSUMPÇÃO (2011), basement depth obtained by BRAGA & SIQUEIRA (1996) in area of the seismic stations location (between 2.5 and $5\ km$) would be reflecting the density contrast in depth. The same is true for the long wavelength component from M3 anomaly whose magnetic source is included in deep source ensemble (Region 1 from power spectrum) an average depth of $6\ km$. The short wavelength component from M3 anomaly would be related to the intermediate or shallow sources, region 2 and 3 from power spectrum. In addition, shallow magnetic sources ensemble depth ($\sim 270\ m$) and the depths obtained by the Werner solutions ($\sim 290\ m$) are relatively concordant with the depths obtained by BARROS & ASSUMPÇÃO (2011) by seismic method ($\sim 360\ m$). Therefore, our study corroborates the depth estimation values obtained by gravimetric method (BRAGA & SIQUEIRA, 1996) and by seismic method (BARROS & ASSUMPÇÃO, 2011).

Another point of convergence between our work and BARROS & ASSUMPÇÃO's results concerns the tendency to basement deepening southwards. Although the depth values estimated in our study are in agreement with the values obtained by BARROS & ASSUMPÇÃO (2011) in terms of mean values, these values are not agree when considering the spatial distribution , being impossible to state, based on Werner solutions, that there is an increase in sedimentary package thickness southwards. However, such an assertion may be sustained considering basement and sedimentary domains are clearly discernible: the first, situated on north, is characterized by a more wrinkled pattern, while the second, situated on south, shows a smoother pattern. Within the basement domain, we can see a complex pattern of linear magnetic anomalies which preferred direction appears to be E-W. This seems to be the basement general direction. These directions are very similar to structures with ENE-WSW orientation which are mentioned by BARROS & ASSUMPÇÃO (2011).

The exposures described in this study confirm the usefulness airborne magnetic field data interpretation applied in sedimentary basin studies. Using the Caiabis Basin as instance, it was possible to obtain evidence on some aspects related to basin. It is hoped our study may encourage the development of further studies aiming geological investigation and geophysical aspects in the region.

ACKNOWLEDGMENTS

We are grateful to the Remote Sensing and Geophysics Division of the Mineral Resource Research Company / Geological Survey of Brazil for providing the airborne geophysical data that were used in the present work.

REFERENCES

BAHIA, R. B. C.; MARTINS-NETO, M. A.; BARBOSA, M. S. C.; PEDREIRA, A. J. (2005). Análise da evolução tectonossedimentar da Bacia dos Parecis através de Métodos Potenciais. *Revista Brasileira de Geociências*, **37(4)**, 639–649.

BARROS, L. V.; ASSUMPÇÃO, M. (2011). Basement depths in the Parecis Basin Amazon with receiver functions from small local earthquarkes in the Porto dos Gaúchos seismic zone. *Journal of South American Earth Sciences*, **32**, 142–151.

BRAGA, L. F. S.; SIQUEIRA, L. P. (1996). Three dimensional gravity modeling of the basement topography beneath Parecis Basin, Brazil, constrained by DBNM, spectral estimates of depth to magnetic sources. *In: 5th Latin Amer. Petr. Cong. Rio de Janeiro, Brazil*.

CLARK, D. A. (1997). Magnetic petrophysics and magnetic petrology: aids to geological interpretation of magnetic surveys. *Journal of Australian Geological & Geophysical*, **17(2)**, 83–103.

FARIA, H. P. A. (2015). Caracterização de domínios tectono - geofísicos na Bacia dos Parecis com base em dados de métodos potenciais. Dissertação de Mestrado, Instituto de Geociências, Universidade de Brasília. 142 pp.

FRASCA, A. A.; BORGES, F. R. (2005). Programa Levantamentos Geológicos Básicos do Brasil - PLGB. Projeto Província Mineral de Alta Floresta (PROMIN ALTA FLORESTA). Geologia e Recursos Minerais da Folha Ilha 24 de Maio SC.21-Z-A. Brasília, CPRM.

GUNN, P. J. (1997). Regional magnetic and gravity responses of extensional sedimentary basins. *Journal of Australian Geology & Geophysics*, **17(2)**, 115–131.

JOHSON, A.; CHEESEMAN, S.; FERRIS, J. (1999). Improved compilation of Antartic Peninsula magnetic data by new interactive grid suturing and blending methods. *Annali Di Geofisica*, **42(2)**, 249–259.

KU, C. C.; SHARP, J. A. (1983). Werner deconvolution for automated magnetic interpretation and its refinement using Marquardt inverse modeling. *Geophysics*, **48**, 754–774.

LEITE, J. A. D.; SAES, G. S. (2011). Geocronologia Pb/Pb de zircões detríticos e análise estratigráfica das coberturas sedimentares proterozóicas do sudoeste do Cráton Amazõnico. *Revista do Instituto de Geociências da USP*, **3**, 113–127.

NABIGHIAN, M. N. (1972). The analytic signal of two-dimensional magnetic bodies with polygonal cross-section: Its properties and use for automated anomaly interpretation. *Geophysics*, **37(3)**, 507–517.

PAINE, J.; HAEDERLE, M.; FLIS, M. (2005). Using transformed TMI data to invert for remanently magnetized bodies. *Exploration Geophysics*, **32**, 238–242.

RAO, B. S. R.; BHIMASANKARAM, V. L. S.(1961). Studies on magnetic properties in relation to magnetic prospecting of Kodur Magnanese Belt: Part III - Correlation of the field results with laboratory studies. *Bull. Nat. Inst. Sci India*, **27(3)**, 207–215.

ROEST, W. R.; VERHOEF, J.; PILKINGTON, M. (1992). Magnetic interpretation using the 3-D analytic signal. *Geophysics*, **57**, 116–125.

SANTOS, H. S.; FLEXOR, J. M. (2012). Geoelectric directionality of a magnetotelluric (MT) survey in the Parecis Basin, Brazil. *Revista Brasileira de Geofísica*, **30(1)**, 81–92.

SILVA, G. H. (1980). Geologia. In: Projeto RADAMBRASIL. Folha SC 21 Juruena, MME. *International Workshop on Gravity, Electrical & Methods and Their Applications*, , 21–116.

SIQUEIRA, L. P. (1989). Bacia dos Parecis. *Boletim de Geociências da Petrobrás*, **3**, 3–16.

SOUZA, J. O.; ABREU FILHO, W.(2007). Geologia e Recursos Minerais da Folha Tapaiúna SC.21-Y-B. *CPRM, Goiânia*.

SPECTOR, A.; GRANT, F. S. (1970). Statistical Models for Interpreting Aeromagnetic Data. *Geophysics*, **55(2)**, 393–402.

WERNER, S. (1955). Interpretation of magnetic anomalies of sheet-like bodies. *Sveriges Geologiska Undersokning, Series C, Arsbok*, **43**, 6.

UHLEIN, A. et al.(2015). Análise estratigráfica de Bacias Rifte Paleo-Mesoproterozóicas dos Crátons Amazõnico e São Francisco, Brasil. *Revista Geonomos*, **23**.