Brazilian Journal of Geophysics 42 (2024), 2, 1-25
Brazilian Geophysical Society
ISSN 2764-8044
DOI: 10.22564/brjg.v42i2.2321

THE MAGNETIC ANOMALY MAP OF PARANÁ STATE: AN INTEGRATION OF AIRBORNE SURVEYS PERFORMED OVER THE YEARS

Alessandra Bongiolo[1*], Luizemara Szameitat[2], Rafael Ribeiro Severino[3]
Mariane Brumatti[4] André Luis Spisila[4] Francisco José Fonseca Ferreira[1],
Pedro Baldessar Netto[1] and Eros Kerouak Cordeiro Pereira[1]

[1] Universidade Federal do Paraná - UFPR, Curitiba, PR, Brazil
[2]Universidade do Estado do Rio de Janeiro - UERJ, Rio de Janeiro, RJ, Brazil
[3]Serviço Geológico do Brasil - SGB, São Paulo, SP, Brazil
[4]Serviço Geológico do Brasil - SGB, Curitiba, PR, Brazil

*Corresponding author email: alebongiolo@ufpr.br

ABSTRACT. Over the last decades, several aerial survey campaigns have been conducted in the State of Paraná. However, we did not have a complete magnetic data integration and analysis focused on the Paraná's geological context. Therefore, the main objective of this work is to provide the integration of all available data and realize a general analysis to make the Integrated Magnetic Map of the Paraná State, in collaboration with the Geological Survey of Brazil (SGB-CPRM). After integrate the data we have applied processing techniques on public airborne magnetic data, available from the Geological Survey of Brazil database (GeoSGB). For this integration, it was used the minimum curvature interpolation, with cell sizes according to each survey. All gridded data was extrapolated upward from the original height to the altitude of 1800 m. Afterwards, we applied the upward continuation for 2700 m and the following filters: vertical gradient (VDR), total horizontal derivative (THDR), analytic signal (AS), or tilt derivative (TDR), tilt angle of the horizontal derivative (TAHG) and vertical integral of the analytic signal (VIAS). The final results provide valuable maps (and grids) that can be used by the community for future works. In this work we tried to do a simple overview of the structural framework of Paraná State, representing the main magnetic structures of the Paraná State basement and compare them with the most important structures already mapped in surface over the years. All the data present in this work and other filters tests are available and can be access in the supplementary material (https://acervodigital.ufpr.br https://hdl.handle.net/1884/89075 and also at zenodo repository https://doi.org/10.5281/zenodo.12820642).

Keywords: airborne magnetometry; structural geophysical mapping; data integration; Ponta Grossa dyke swarm; magnetic data processing.

INTRODUCTION

The State of Paraná (Southern Brazil) has remarkable geological diversity, including the outcropping of the southernmost Ribeira orogenic belt, Luiz Alves cratonic fragment and Paranapanema continental block, and the Ponta Grossa Dyke Swarm (PGDS), and the Paleozoic Paraná Basin dominates the sedimentary cover (Figure 1). Since most of the basement is overburden by the sedimentary cover, geophysical methods, such as airborne magnetometry, work as an essential tool for unravelling the hidden structures, and mapping the lateral continuation of outcropping large-scale geological features. In the last decades, efforts have been done for obtaining geophysical data in the Paraná State area, in order to get a comprehensive view of the subsurface geological setting.

As previous studies, we can cite the Simões Neto (2007), who made the (partial) Phanerozoic Magnetic Map of the state, and the data was later supplemented with geophysical work on the Paraná Basin from the Revitalization Program for Exploration and Production of Oil and Natural Gas in Onshore Areas - REATE (Souza Filho & Szameitat, 2022) for processing and interpretation. Other previous magnetic studies revealed the importance of mapping magnetic structures for the understanding of magmatic processes and the close relation between basement structures and the Paleozoic sedimentary evolution (e.g., Ferreira et al., 1981; Pinto & Vidotti, 2019; Souza Filho & Szameitat, 2022). Magnetic techniques were also used for the analysis of Cenozoic tectonic movements near Ponta Grossa Dyke Swarm (Santos et al., 2021).

In this work, we provide the integration and realize a general analysis to build the Integrated Aeromagnetic Map of the Paraná State using the previous public data available from the SGB-CPRM. This aeromagnetic integrated data will be available in the form of spreadsheets and georeferenced images that can be used, in future works in the state. Even that it was performed tests with enhanced filters, (also available), as well as automated and manual tracings of structures relating to magnetic anomaly.

A simple qualitative interpretations of magnetic anomaly enhanced features have been done comparing the surface and subsurface structures mapped by several authors and the SGB magnetic map (Bongiolo et al, 2023) to compare and understand the structural framework of the Paraná State.

Future studies of tectonic evolution, can use the data of this work to investigate and better understand the structural elements and features that characterize and shape the state's geology. Observing and understanding these structural elements is extremely important for geological mapping and the exploration of natural and mineral resources. For instance, patterns of structural lineaments and fault systems can lead to the formation of structural traps for the economic concentration of energy resources, as well as indicating aquifer recharge and discharge zones. The dyke swarm of the Ponta Grossa Arch is of great importance in the region because, as well as being very thick and extensive, they have a preferential NW orientation, which coincides with major structures in the area.

GEOLOGICAL CONTEXT

The Paraná Shield

The Paraná Shield comprehends the outcropping basement of the state, which is part of the Southern Ribeira Belt, in the Mantiqueira tectonic province (Almeida et al., 1973, 1977). It comprises an orogen resulting from the collision between the Paranapanema and Luis Alves cratons, due to the amalgamation of the Western Gondwana Supercontinent in the Brazilian-Pan-African Orogeny (e.g., Brito Neves et al., 1999; Heilbron et al., 2000, 2004; Basei et al., 2009; Passarelli et al., 2011). Remarkable morphological features in the outcropping basement are the Serra do Mar and the First Paraná Plateau in the eastern part.

Regarding the major forming tectonic units, there are four different terranes: Luis Alves, Paranaguá, Curitiba and Apiaí (Besser et al., 2021; Brumatti et al., 2023). The granulite gneisses of the Luis Alves Terrain, of Archaean age (Hartmann et al., 2000; Passarelli et al., 2018), represent the oldest records. Deformed gneisses and granitoids, representatives of the Paleoproterozoic basement, occur mainly in the Curitiba Terrain (Siga Jr. et al., 1993; 1995), and Mesoproterozoic metavolcano-sedimentary sequences, some containing important polymetallic mineralization, are widely distributed in the Apiaí Terrain (Campanha & Sadowski, 1999; Faleiros et al., 2012; Campanha et al., 2015). Records from the Neoproterozoic include carbonate platform deposits with preserved sedimentary structures, such as stromatolites and stratifications (Reis Neto, 1994; Santos et al., 2021).

The cited terranes were amalgamated by collision between 630 and 600 Ma, with the consequent development of subduction to the NW and transcurrent shear zones in a NE-SW direction (Prazeres Filho, 2000; Harara, 2001; Faleiros et al., 2011a). The syn- to post-collisional period was marked by significant arc-related granitic magmas, culminating in large batholiths. In the post-collisional stage (ca. 590-560 Ma), distensional stress regime generated a large rift system, the Southeastern South America (Riccomini, 1989; Passarelli et al., 2011).

Ponta Grossa Dyke Swarm (PGDS) and regional structural patterns

In the consolidated orogenic belt, there was the intrusion of basic and alkaline rocks associated with the Mesozoic tectonic processes and magmatic events of the Paraná Basin (Licht & Arioli, 2018). The PGDS is a remarkable network of sheet-like tholeiitic intrusions across the outcropping basement and the Paraná Basin. The dyke swarm is associated to the Atlantic opening, where it is linked with other dyke complexes, and also can be considered as part of a triple junction (Coutinho, 2008). The main age interval of the PGDS can be estimated as ca. 131-129 Ma, with magmatic peak about 130.5 Ma (Renne et al., 1996).

Most of dykes in Paraná State are oriented according to NW-SE regional orientation of brittle basement structures, which are pervasive in the Paraná Basin (NW oriented structures, Figure 2). For example, NW-SE central area of PGDS is inherited at least since Devonian (Pinto, 2019; Souza Filho & Szameitat, 2022). Dykes of PGDS have concentrated occurrence about the axial area of Ponta Grossa Arch, a crustal flexure from the coastline to the beginning of Paraná Basin.

The PGDS was also associated with higher groundwater productivity, suggesting that the damage zones surrounding those dykes enhanced the groundwater flow (Cavalcante et al., 2020). Due to this, close relation, governmental efforts have been done for improving the magnetic mapping of dykes for the groundwater management of fractured aquifers (e.g., Souza et al., 2023).

NE-SW fault zones occur in the whole state, and follow the major orientation of Proterozoic terranes (Figure 2). We do not know details about the nature of the hidden basement terranes under Paraná Basin. However, we assume that the intense compression due to the collision of Angolan Craton lead an intense imprint of a brittle network to the whole area. The continental collision also enforced the NE-SW trend and intense NE-SW transcurrent movements (800-500 Ma; Faleiros et al., 2022), among São Francisco Craton, Paranapanema Block, and Angolan Craton, in the south-southeastern Brazilian basement. Paranapanema Block is a continental segment, which may acted as a paleo plate in the Brazilian orogenic cycle. Several works have been interpreted the crustal architecture of this area, as a unique paleoplate (e.g., Mantovani et al., 2005; Cordani et al., 2016) or fragmented blocks (e.g., Milani & Ramos, 1998). Such block is overburden in the westernmost area of Paraná State.

Additionally, a bunch of E-W tectonic trends is also encountered, especially in the northern part of the state. Those faults are often associated to post-orogenic transcurrent movements, which may have been active up to Cenozoic (Pinheiro & Cianfarra, 2021; Santos et al., 2021). The approximately E-W oriented faults are in agreement with the regional neotectonic stress-field (Pinheiro & Cianfarra, 2021).

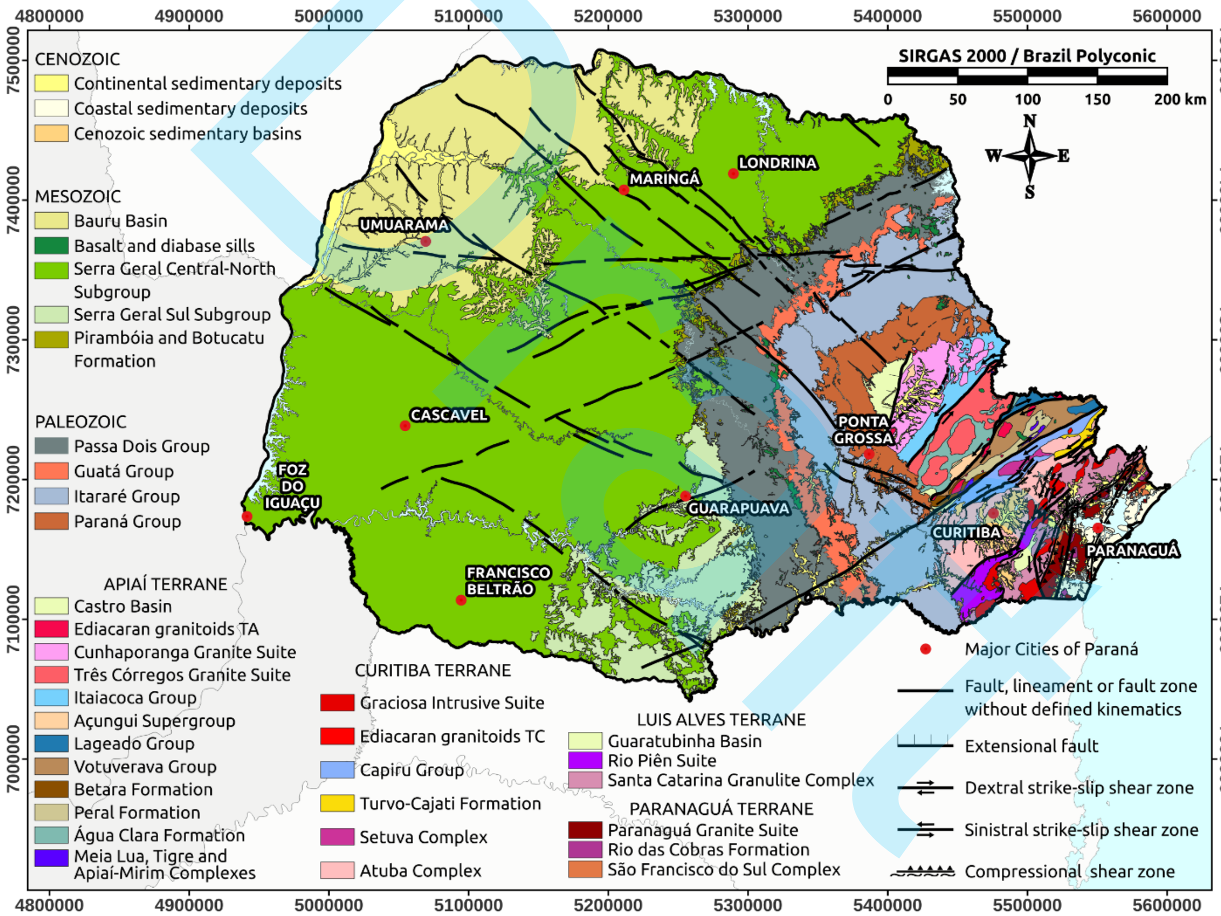

Figure 1: Simplified Geological Map of the Paraná State (adapted from Besser et al., 2021).

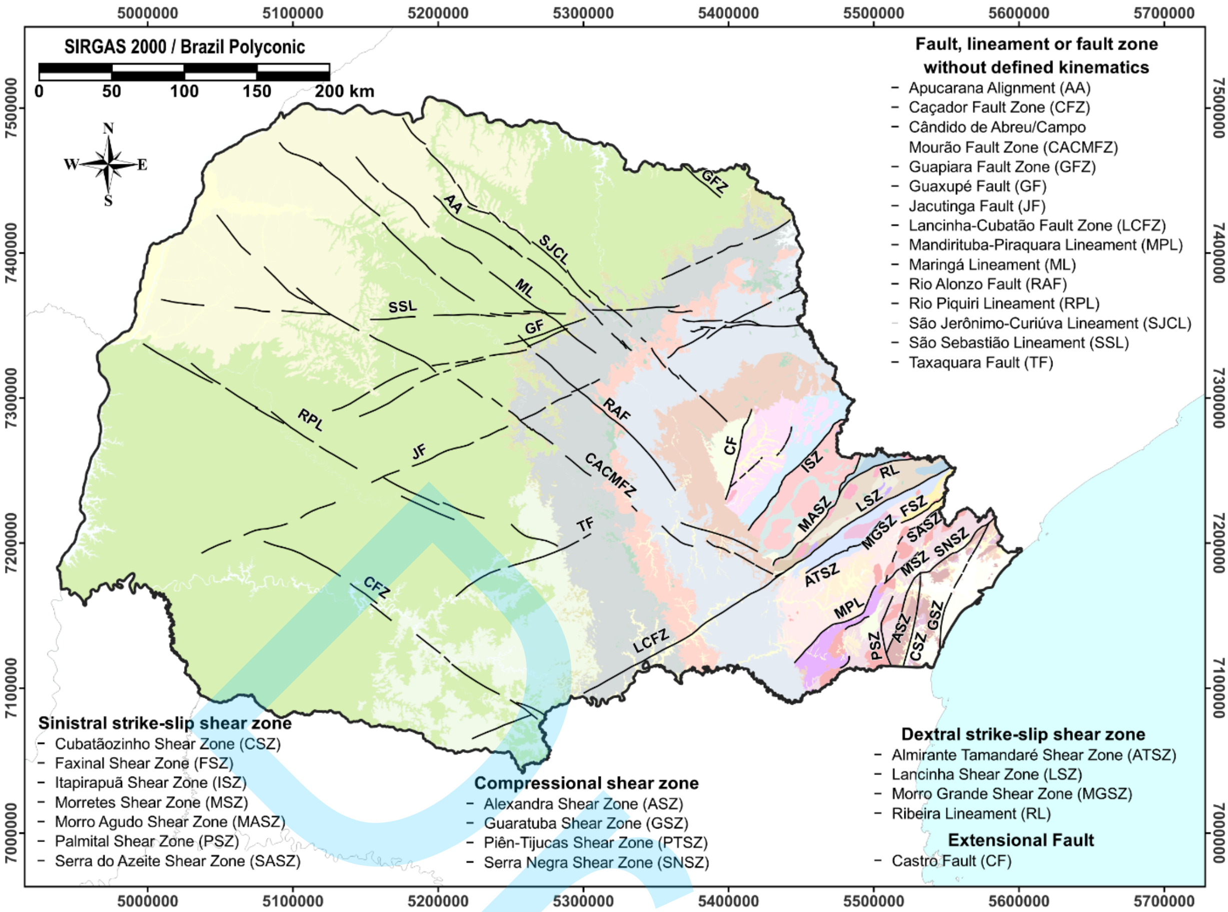

Figure 2: Structural framework of Paraná State (adapted from Besser et al., 2021).

Paraná and Bauru basins

The sedimentary coverage of the Paraná Basin comprises the Second Paraná Plateau, while the volcanic rocks of the Paraná Basin and the Bauru Basin correspond to the Third Paraná Plateau.

The Paraná Basin is located in the South American Platform, whose formation began in the Siluriano period and lasted until the Lower Cretaceous. It has an approximately elliptical shape, and covers an area of around 1.5 million square kilometers. (MINEROPAR, 2001; Milani et al., 2007). The first sedimentary successions were possibly accommodated in a central rift (Marques et al., 1993; Milani, 2004), elongated in a NE-SW direction, associated to reactivated crustal weakness of the Precambrian basement (Almeida, 1980; Milani, 1997). Important subsidence mechanisms may be a lithospheric flexure (Milani, 1997) and/or contraction due to the tectono-magmatic phenomena of the Brazilian Cycle (Zalán et al., 1990), and the influence of the Andean subduction dynamics (Milani & Ramos, 1998). The Paraná Basin borders are mostly erosive, associated to fault zones and arcuate crustal structures (Zalán et al., 1990; Milani, 2004). In this context, the eastward Paraná State encompasses the axis of the Ponta Grossa Arch, a significant crustal bending structure in the eastern edge of Paraná Basin.

In the Lower Cretaceous, the sedimentation processes were interrupted by the magmatism of the Serra Geral Group, as part of the Paraná-Etendeka Large Igneous Province (PELIP) (e.g. Besser et al., 2024), due to the continental rupture of Gondwana and the opening of the South Atlantic Ocean (Milani et al., 2007). The eastern edge of the lava field marks the escarpment of the Third Paraná Plateau (Escarpment of the Serra Geral; Maack, 1968; deep green on Figure 2), which southeastward concave aspect is given by the Ponta Grossa Arch.

As a recent sedimentary package, the Bauru Basin started in the Late Cretaceous, located in the northwest of the Paraná State. It was developed in an extensive area of volcanic terrain that acted as the depocenter, associated to the Caiuá desertic environment (Fernandes & Ribeiro, 2015).

METHODS

Airborne Magnetic Data

Filtering methods are commonly applied to potential field's data for mapping geological contacts and faults. In general, the qualitative interpretation of aeromagnetic data is based on determining the maximum amplitude of a function, such as the horizontal and vertical gradients and the analytical signal (Silva, 2007).

Magnetometry is used for investigation of surface and subsurface geology using the Earth's magnetic field as a function of the magnetic properties of rocks (Dentith et al. 2014). This method is commonly used to investigate subsurface geological structures, such as dykes, faults and geological contacts. There are other applications as well, such as prospecting for deposits of ferromagnetic minerals and oil, locating buried or submerged metallic structures, among other various purposes.

Data Integration

The raw datasets were obtained from the Repositório Institucional de Geociências (https://rigeo.cprm.gov.br/) and GeoSGB (https://geosgb.sgb.gov.br/geosgb/) as .xyz files. All applied surveys can be seen in Figure 3, and relevant survey parameters are listed in Table 1. We used the Grid Knit module in the Oasis Montaj software for performing a multistep merging of magnetic grids. The interpolated datasets were integrated following the sequence presented in Table 1.

The data treatment started with a critical analysis of the data. The total field magnetic anomaly was gridded from databases with the cell size as described in the source (head of ASCII files or report; "Original grid cell size" column in Table 1). In some cases, gridded data with the original cell size was not suitable for merging with other grids, due to mathematical artifacts or high noise. In these cases, we have tested larger space values. In the Rio Ivaí and Botucatu areas, the adjusted cell size was ¼ of the line spacing, consistent with other cell sizes employed in potential field methods. The Serra do Mar Sul has linear NW-SE artifacts from the acquired lines; therefore, it was gridded with a line spacing of 500 m in an attempt to reduce these artifacts. This adjustment was applied only in the gap between the Paraná-Santa Catarina and Ponta Grossa-Criciúma acquisitions (green area, Figure 3). Although it may appear 'too large' for data gridding, using half of the sample spacing is defensible by considering the Nyquist theorem (e.g., Lafehr & Nabighian, 2012). Since the highest survey (0001_Bacia_do_Paraná_28058) has

1800m of nominal altitude, all of gridded data were transformed by the upward continuation filter (up to 1800m) prior to the grid merging. The interpolated datasets were integrated following the sequence presented in Table 1.

Table 1: Integrated aeromagnetic surveys and their main characteristics. “Original grid cell size” refers to the value from the data source, and “Applied grid cell size” was the adjusted cell size for mitigating mathematical artifacts.

N.º	Location	Survey	Year	Line spacing (m)	Nominal altitude (m)	Original grid cell size (m)	Applied grid cell size (m)
1	Paraná Basin	0001_Bacia_do_Paraná_28058	2010	6000	1800	1400	1400
2	Iguaçu River	4023 (Petrobras) / 4098 (SAMMP)	1980	2000	500	400	400
3	Paraná-Santa Catarina	Projeto Paraná-Santa Catarina	2011	500	100	125	125
4	Paraná Basin	4012 (Petrobras) / 4032 (SAMMP)	1973	7000	1500	1400	1400
5	West Border of Paraná Basin	4051, 4052, 4053 (Petrobras) / 4246, 4101, 4245 (SAMMP)	1989	3000	1000	600	600
6	Ivaí River	4025 (Petrobras) / 4111 (SAMMP)	1981	2000	450	400	500
7	Ponta Grossa - Criciúma	4258 (SAMMP)	1971	1000	120	*	200
8	Serra do Mar Sul	4029 (SAMMP) / 1025 (CPRM)	1979	1000	200	**	500
9	Botucatu	4019 (Petrobras) / 4099 (SAMMP)	1980	2000	450	400	500

**data available as digitalized curves of isovalues. **not specified.*

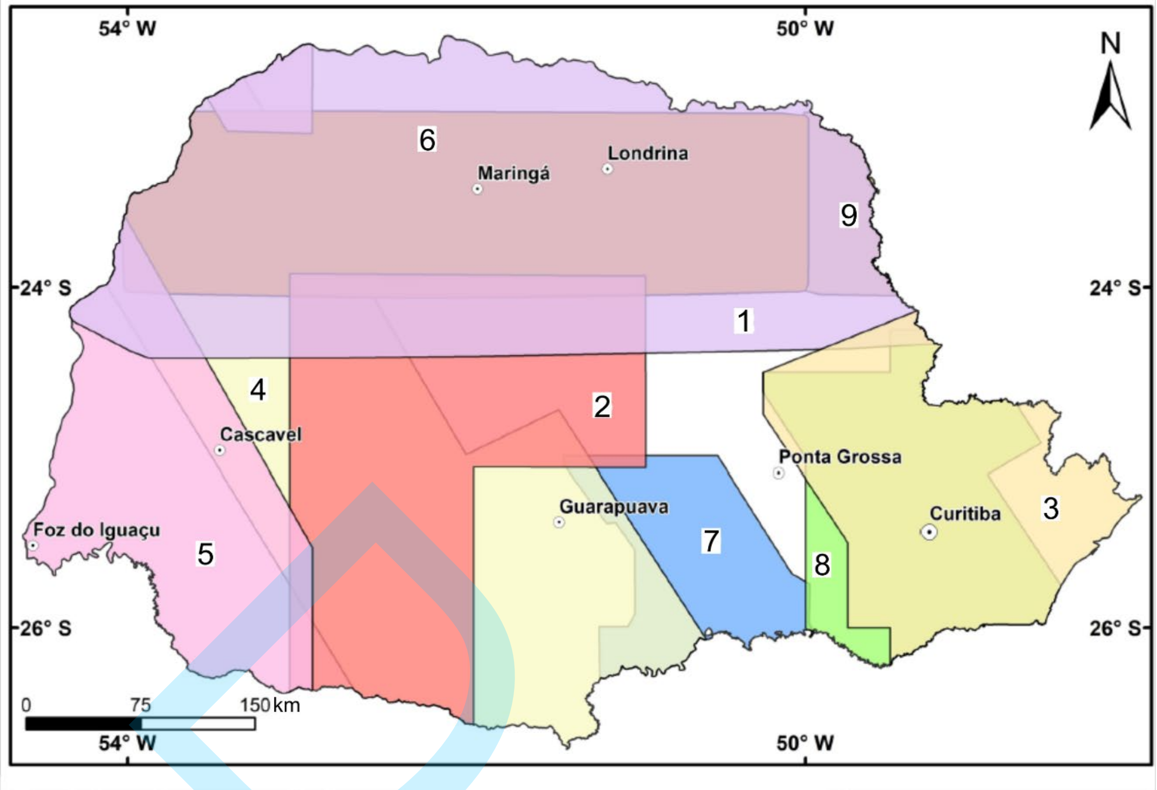

Figure 3: Location map of the surveys listed in Table 1.

Magnetic Data Filtering

In order to assist the development of this research in conceptual terms and in the supply of images and data, we applied filtering techniques after integrate all the surveys. Since most of the applied filters are based on derivatives, which enhances the high frequency noising, we opted for continuing the integrated data upwards. Therefore, the filters were applied over the total field anomaly upwarded to 2700 m, in order to mitigate noising effects.

Several techniques were used to enhance magnetic anomalies, including the vertical gradient (VDR), horizontal derivatives (Gx and Gy), total horizontal derivative (THDR), analytic signal (AS), tilt derivative (TDR), tilt derivative of the horizontal derivative (TAHG), and vertical integral of the analytic signal (VIAS).

Upward continuations

As is well known, the upward continuation procedure (Gunn, 1975 apud Silva, 2005) simulates the acquisition of magnetic field data at levels higher than the original, which removes or at least minimizes signals from shallow sources and noise. This transformation is essential for data integration, since the original gridded data was at different altitudes.

$$U(P) = \frac{1}{4\pi}\int_{s} \left(\frac{1}{r}\frac{\partial U}{\partial n} - U\frac{\partial}{\partial n}\frac{1}{r}\right) dS$$

Vertical Derivative (VDR)

The vertical gradient (Evjen, 1936), also known as the first vertical derivative, represents the rate of change in the potential field with respect to the 'z' direction. It is typically calculated in the frequency domain, taking into account the harmonic nature of the potential field. Since large waveforms, produced by deep sources, exhibit a relatively small spatial change ratio, the vertical derivative tends to emphasize high frequencies originating from shallow sources.

$$VDR = \frac{\partial \Delta T}{\partial z} = \lim_{\Delta z \to 0} \frac{\Delta T(x,y,z) - \Delta T(x,y,z-\Delta z)}{\Delta z}$$

Total Horizontal Derivative (THDR)

The calculation of the horizontal derivative of the magnetic or gravimetric field (THDR; Cordell & Grauch, 1985) enables an analysis of the surface geometry of the regular mesh, indicating abrupt changes in the gradient of these potential fields, which can be caused by a jump in the average value or by the presence of a peak in the data. They are based on the results of the slope (first derivative) or the rate of change of the gradient (second derivative). THDR can use the resulting mesh to identify abrupt changes in geological fields, which provides accurate results for geological mapping.

$$THDR(x,y) = \left[\left(\frac{\partial g_z(x,y)}{\partial x}\right)^2 + \left(\frac{\partial g_z(x,y)}{\partial y}\right)^2\right]^{1/2}$$

Analytical Signal (AS)

The analytical signal (AS; Nabighian, 1972; Roest et al., 1992) is a function related to the derivatives in the x, y and z directions of the magnetic or gravimetric field. AS are used to detect and outline source borders (Gunn, 1997 a, b), although they are effective for this purpose only in the case of shallow sources (Li, 2006). Additionally, the half-widths of these peaks can be related to the depth of vertical magnetic and gravimetric contacts. However, Li (2006) demonstrated that AS is not entirely independent of magnetization. In this work, relatively thin magnetized structures could be located using AS filtering.

$$|A(x,y,z)| = \sqrt{\left(\frac{\partial \Delta T}{\partial x}\right)^2 + \left(\frac{\partial \Delta T}{\partial y}\right)^2 + \left(\frac{\partial \Delta T}{\partial z}\right)^2}$$

Tilt Derivative (TDR)

The tilt derivative (TDR; Miller & Singh, 1994) represents the quotients of the arctangent of the VDR divided by the modulus of the THDR. This filter can detect potential sources of field anomalies and provide information on their horizontal extent. It has the property of being positive above the source, crossing zero near the edges, and being negative outside the source.

The TDR has the additional attribute, unique among the various edge detection methods, of responding equally well to shallow and deep sources. For this reason, it is able to detect the presence of subtle deep sources, which are often masked by the profusion of responses from shallower sources, especially in strongly magnetized areas.

$$TDR = tan^{-1}\left(\frac{\partial \Delta T}{THDR}\right)$$

Tilt derivative of the Horizontal Derivative (TAHG)

The TAHG is obtained by taking the arctangent of the VDR of the THDR, divided by the modulus of the THDR. (Ferreira et al., 2010, 2013) is recommended for mapping mineral exploration structures and targets, highlights features that may not be clearly identified by previous methods. One of the advantages of the method, according to Ferreira et al. (2010, 2013), is that TAHG denotes better resolution of body boundaries, as TDR equalizes THDR amplitudes. Thus, this method highlights the responses of bodies located at varying depths simultaneously.

$$TAGH = tan^{-1}\left(\frac{\frac{\partial THDR}{\partial z}}{\sqrt{\left(\frac{\partial THDR}{\partial x}\right)^2 + \left(\frac{\partial THDR}{\partial y}\right)^2}}\right)$$

Vertical Integral of the Analytic Signal (VIAS)

The vertical integration of magnetic data enhances the magnetic response of deep sources (Silva, 1996). The combination with AS data tends to be suitable for interpretation and modeling, as the anomalies tend to be centered on their magnetic sources (Paine et al., 2001). Bongiolo et al. (2022) have demonstrated that VIAS can be useful for estimating unknown targets. In this work, the application of VIAS is restricted to picturing regional features, especially the dyke swarm.

$$VIAS = \int_0^\infty \sqrt{\left(\frac{\partial \Delta T}{\partial x}\right)^2 + \left(\frac{\partial \Delta T}{\partial y}\right)^2 + \left(\frac{\partial \Delta T}{\partial z}\right)^2}\, dz$$

Automated and manual tracking of magnetic features

Blakely & Simpson (1986) describe a technique that identifies anomaly peaks from a grid file and automatically detects these sources, while avoiding the influence of high-frequency noise. As a result, the algorithm generates punctual solutions (represented as circular symbols) over geophysical peaks. Generally, we consider clusters of symbols that exhibit high linearity to indicate a more feasible representation of geological structures.

We interpreted major tectonic structures that are identifiable in the magnetic grids. We proceeded automated in order to represent possible geological structures, where the “grid peaks” technique was used for initial mapping. After the automated analysis, we proceeded a manual tracing of lineaments, focusing on possible faults, and large textural domains.

RESULTS AND DISCUSSION

Magnetic maps

The Figure 4 shows the integrated magnetic anomaly map (MA). After the grid merging, the general aspect of the map shows good lateral continuity of elongated and linear magnetic features. Artifacts in the diverse surveyed areas were mitigated, in relation to the previous example of magnetic data integration in Figure 5 (CPRM, 2019). Other types of artifacts from data acquisition and processing were reduced, providing a significant enhancement. For example, the representation of straightforward magnetic features in the dyke swarm, especially in the central-northern area, has notably improved.

In the interpretation of magnetic anomalies, we employed filtering techniques to validate the anomalies from data integration. For the applied filters, the input data was the upward continued data (Figure 6). The Figure 7 represent the filtered grids VDR, THDR, AS, TDR, TAHG, and VIAS. These filtered data highlighted anomalous trends for the comparison with the main geological structures in the Paraná State, taking into account the particularities of each filter.

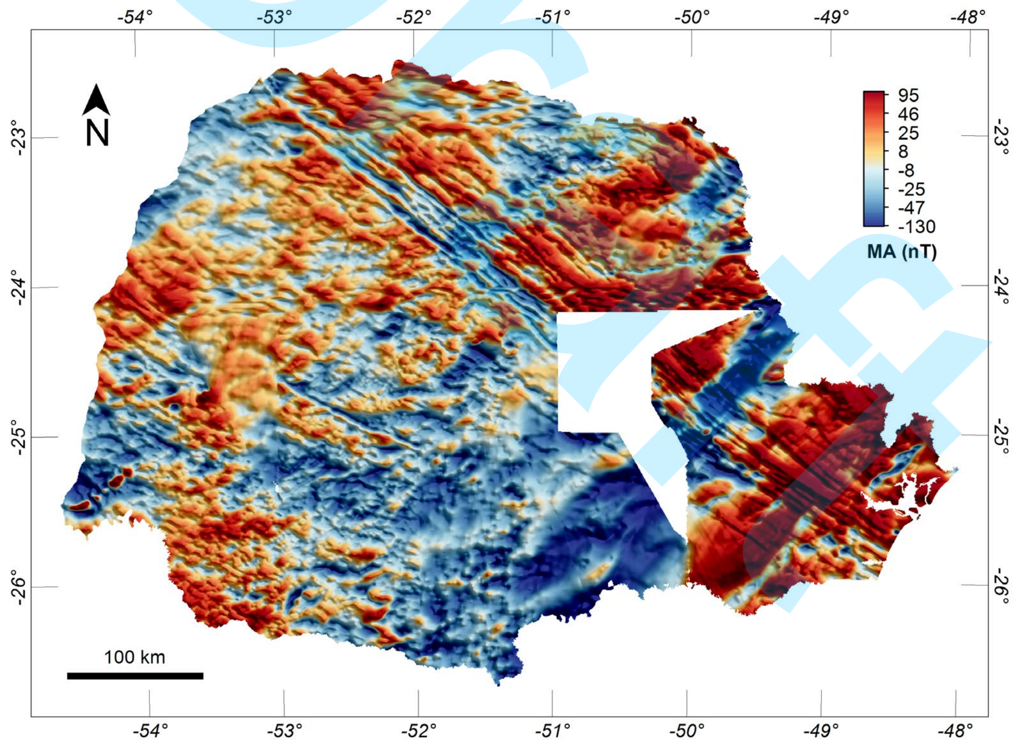

Figure 4. Integrated magnetic anomaly map.

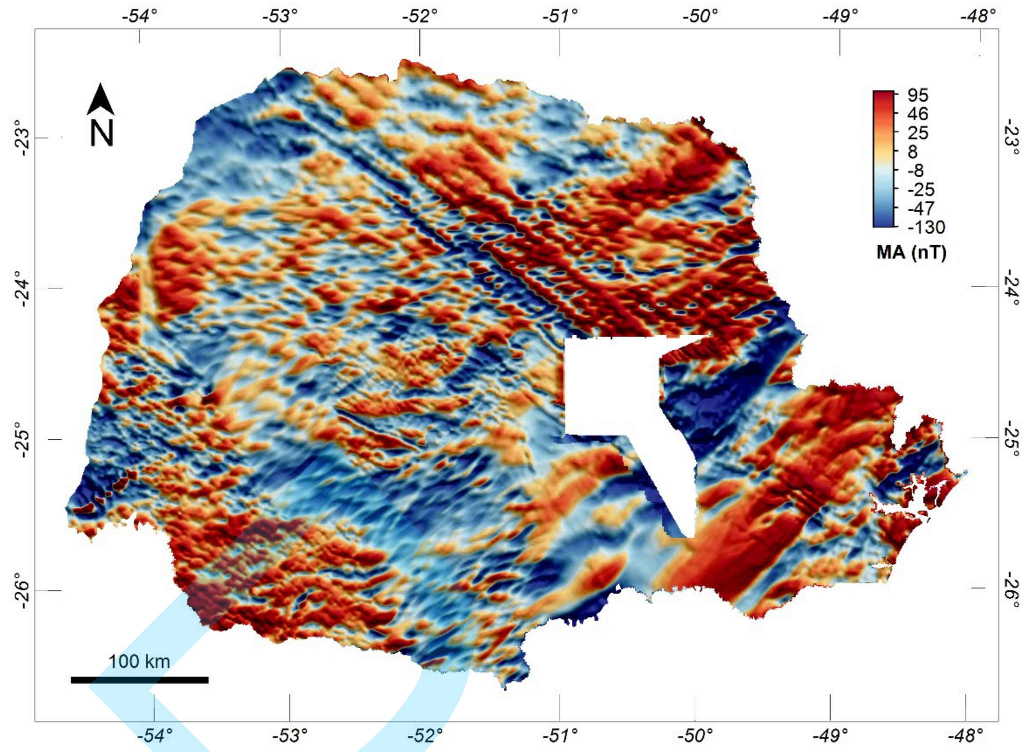

Figure 5. Magnetic anomaly map from previous compilation (CPRM, 2019).

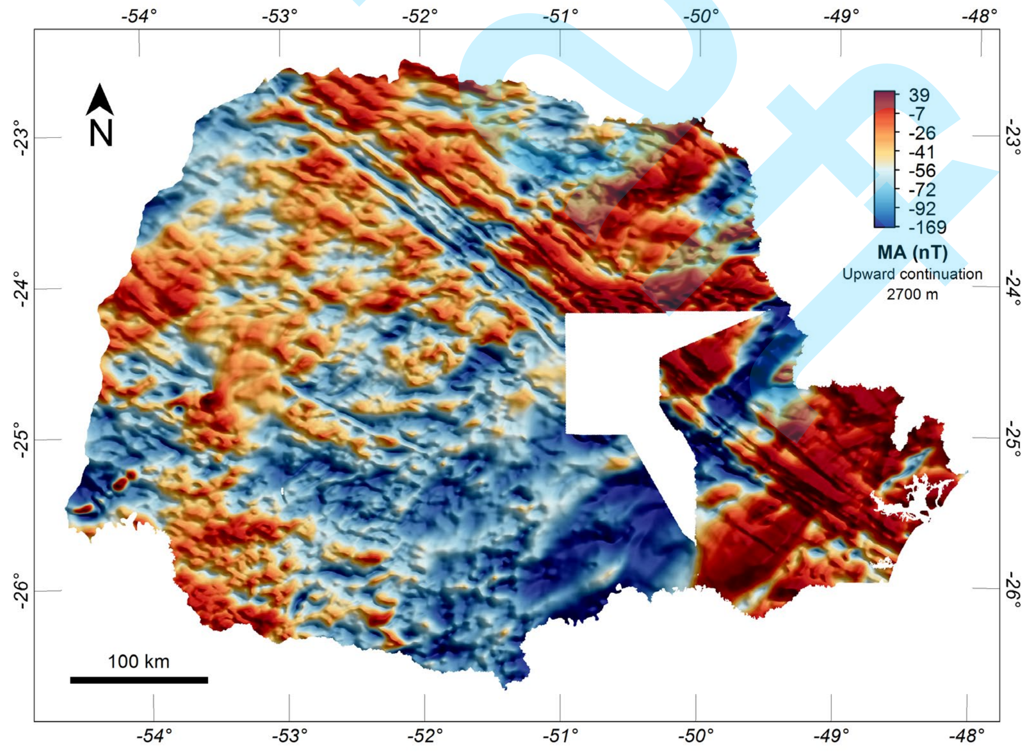

Figure 6. Magnetic anomaly map upward continued to 2700 m.

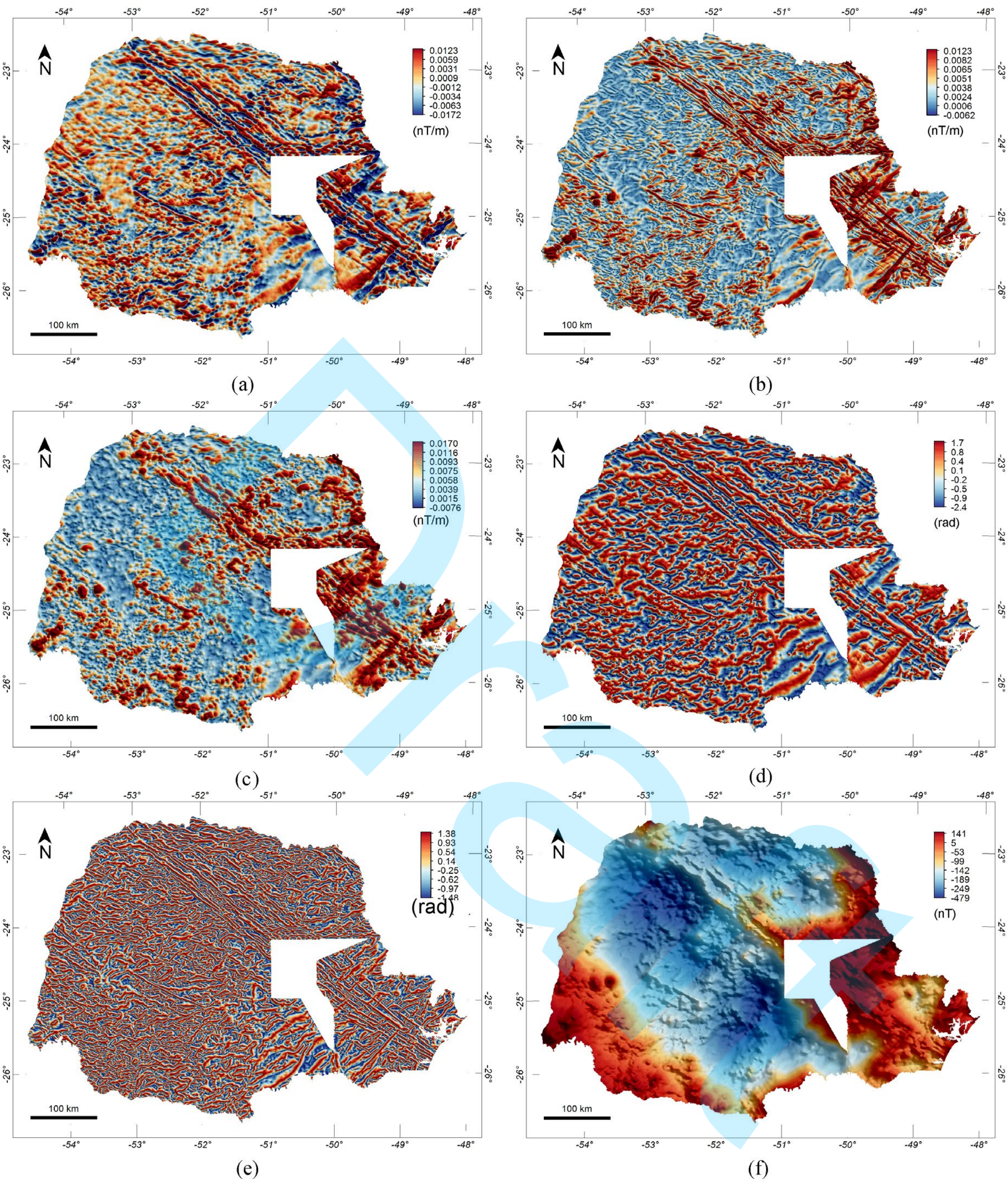

Figure 7. Magnetic maps obtained using the vertical derivative (a), the total horizontal derivative (b), the analytical signal (c), the tilt derivative (d), the tilt angle of the horizontal derivative (e) and the vertical integral of the analytical signal (f) in the Paraná State.

Geological-Geophysical Integration

The Figure 8c illustrates manual interpretation mainly based on MA, but in consonance with filtered maps (Figure 7), and the automatized peaks founded in AS (Figure 8b). Complementarily, Figures 8c and

8d show geological interpretations.

For geophysical interpretation, relevant works in the structural geology of Paraná have been utilized so far, where the main tectonic features and the main lineaments of the state have been mapped: Ferreira 1981, 1982a, 1982b; Simões Neto, 2007; Soares, 1982, 2007; Milani, 2004; Zalán et al, 1987, 1990; CPRM, 2021; and Souza Filho & Szameitat, 2022. In general, there was a good spatial correlation between the geological and geophysical features, with some variations between those authors. In this project, the geological significance of the magnetic domains was due to qualitative correlation with newly geological and structural features of the Paraná State (Besser et al., 2021; figures 1 and 2).

The geophysical structural elements were interpreted as faults, lithological contacts, or magmatic intrusions that have preserved the magnetic susceptibility of the rocks. Lineaments in the southeastern basement have good correlation with mapped NE geological limits. Conversely, in the central-western Paraná State, most of the magnetic lineaments that matched outcropping structures are NW-SE oriented, such as dykes of the PGDS (Figure 2). NW-SE is the major direction of dykes, and it seems to influence the tectonic evolution of Paraná Basin (e.g. Ferreira et al., 1982; Pinto, 2019), even after the emplacement of the dykes swarm (Licht, 2018).

NE-SW orogenic trend is remarkable both in the Paraná shield and beneath Paraná Basin, but the central-western basement has also NNW-SSE orientations. From texture changes in the MA grid, we inferred basement sectors of high magnetization and high frequency anomalies (dark rose in Figure 8c). Although their origin is uncertain, Proterozoic collisional events described in literature (ca. 900-600 Ma) allow us to assume that these sectors are part of hidden collisional structures. Geological context of orogenic roots under Paraná Basin is poorly explored in the literature, but it was suggested by geological interpretations in Milani & Ramos (1998), for instance. Moreover, geophysical soundings of different methods have shown the possibility of hidden oceanic sutures beneath the sedimentary cover (e.g., Padilha et al., 2015; Dragone et al., 2021).

Another example of recurrent orientation is the E-W tendency, recognized in the center-northern geological framework (São Sebastião Lineament, SS in Figure 8). Linear interruptions of anomalies and textures in the central and southern Paraná State suggest E-W lineaments throughout the state. Additionally, high-magnetized sectors inferred in the central-western state are interrupted by an E-W zone of low MA values (Figure 8). Conversely, we have noticed the relative scarcity of large-scale E-W faults in the eastern basement. As a result, it is possible to interpret that the E-W deformation had large influence in the basement formed prior to the Ribeira Belt, at least in Paraná State. Concerning these eastern terranes, recognized lineaments and texture of the magnetic pattern were interpreted as their lateral continuation beneath the Paraná Basin (Figure 8c).

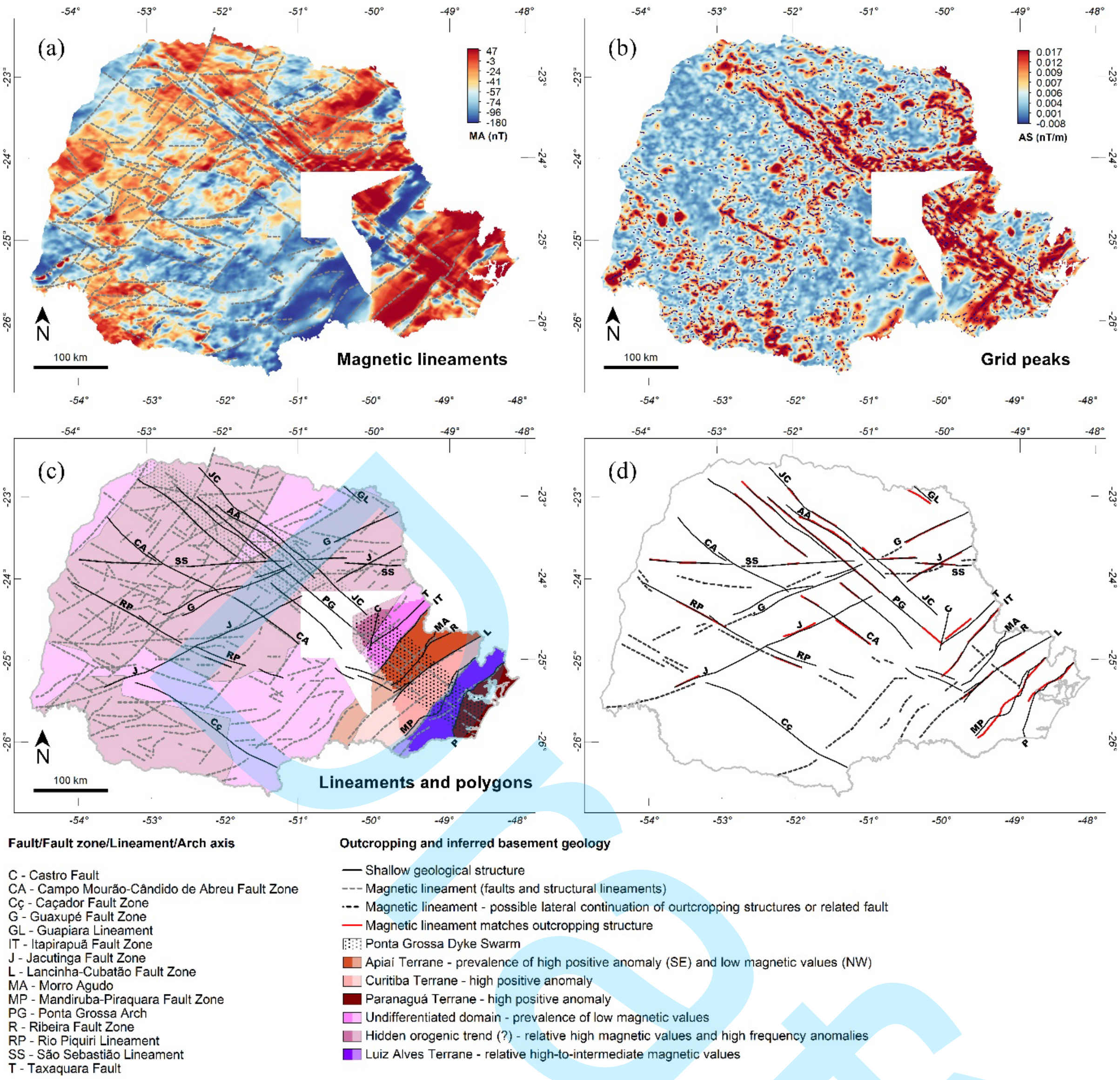

Figure 8. Magnetic anomalies map with manual lineaments (a), semi-automatized pick seeker algorithm (b), and qualitative analysis in (c) and (d). Large geological sectors (c) were interpreted based on textural changes in the magnetic anomaly grid. Part of the magnetic lineaments may represent the lateral continuation of outcropping features (d). Tectonic units of the Proterozoic orogenic basement are shown in vivid colors in the outcropping areas, while basement units covered by the Paraná Basin are depicted in pale colors.

In the comparison with mapped structures, some lineaments are dislocated in relation to outcropping fault or contact (Figure 8c), or they are not recognized in the magnetic map. Based on Potential field theory and Laplace's concepts, we can transform the potential field data to different altitudes, depending on the purpose. On the other hand, upward continuation transformations may result in data have significant loss of high frequency, and the smoothed anomalous grid represents deep structures or shallow structures that persists in greater depths, such as observed for large sheeted dykes. The same effect can be applied for airborne data, in comparison with terrestrial acquisitions. Other limitations are different applied techniques and spatial resolution. As a result, the interpreted features in the integrated data are mostly related to deep magnetic sources, and they may not coincide with the outcropping position of geological features, unless they are vertical or sub-vertical dipping. Despite of those limitations, the obtained magnetic maps agree with the aiming of this project, which intend to provide accessible datasets for the geological community and an integrated view of magnetic geological structures.

CONCLUSIONS

The integration of available geophysical data allowed the advancing of our understanding of geological processes that occurred in the Paraná State. Integrated magnetic maps provide a good view of the subsurface geological framework, especially related to the basement. Those maps are used for identifying geological boundaries, faulting traces, and large magnetized areas that can correspond to geological units. Since the integration was performed at 1800m, the resulting magnetic maps cannot be suitable for interpreting shallow magnetic sources (e.g., thin dykes), unless they persist to greater depth or have enough size (e.g., large dykes). The same observation can be done for the magnetic anomaly continued to the altitude of 2700m and filtered data. Despite of that, we show that it is possible to recognize significant geological features that are linked to the outcropping geology.

The magnetic anomaly map of Paraná State shows better magnetic anomalies lateral continuity, in relation to previous data integration (CPRM, 2019). The good correlation of magnetic anomalies and known geological features indicates that the applied techniques provided a consistent database that can be used by the community for numerous purposes, with emphasis on refining the structural framework of the Paraná State.

The availability of integrated and filtered data may benefit geoscientists who need a brief view of the magnetic signature of their study areas, such as researchers or explorers of mineral exploration and groundwater resource management.

Data and Materials Availability

The resulting magnetic data is available at the UFPR scientific repository https://acervodigital.ufpr.br/ https://hdl.handle.net/1884/89075 and also at zenodo repository https://doi.org/10.5281/zenodo.12820642.

ACKNOWLEDGEMENT

This work in progress is part of the research project entitled "Development and elaboration of the structural geophysical framework of the state of Paraná", which aims to characterize the structural geophysical framework of the state, through qualitative and quantitative interpretations after processing the data from different geophysical methods made available by the Database of the Geological Survey of Brazil (GeoSGB) and other national entities. The authors would like to thank the Universidade Federal do Paraná (UFPR), the Laboratory for Research in Applied Geophysics (LPGA/UFPR), and the Geological Survey of Brazil (SBG), for the continuous support. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001 (L. Szameitat 88887.798323/2022-00).). F.J.F. Ferreira was supported in this research by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) under contract 308956/2022-2.

REFERENCES

Almeida, F. F. M. Tectônica da Bacia do Paraná no Brasil, 1980, relatório nº 14091: 86-137. IPT, São Paulo – SP.

Almeida, F. F. M., G. Amaral, U. G. Cordani and K. Kawashita, 1973, The Precambrian evolution of the South American cratonic margin south of the Amazonas River. In: Nairn, A.E.M., F.G Stille. (Ed.). The ocean basin and margins. New York: Plenum, v. 1, p. 411-446. doi: https://doi.org/10.1007/978-1-4684-3030-1_11

Almeida, F. F. M., Y. Hasui, B. B. Brito Neves and R. A. Fuck, 1977, Províncias estruturais brasileiras. In: Simpósio de Geologia do Nordeste, 8., Campina Grande. Atas… Campina Grande: SBG. 499 p. (Boletim do Núcleo Nordeste da SBG, 6). p. 363-391.

Almeida, R. P., L. Janikian, A. R. Fragoso-Cesar, G. L. Fambrini, 2010, The Ediacaran to Cambrian Rift System of Southeastern South America: Tectonic Implications. The Journal of Geology, v. 118, p.145-161. doi: https://doi.org/10.1086/649817

Baldin, M. T., E. Salamuni, L. E. Lagoeiro, E. Sanches, 2022, High-temperature deformation processes in migmatites from the Atuba Complex, southern Ribeira Belt: Constrains from microstructures and EBSD analyses. Journal of South American Earth Sciences, American Earth Sciences, v.116. doi: https://doi.org/10.1016/j.jsames.2022.103863

Barão, L. M., B. Trzaskos, F. F. Vesely, L. G. Castro, F. J. F. Ferreira, E. M. G. Vasconcellos, T. C. Barbosa, 2017, The role of post-collisional strike-slip tectonics in the geological evolution of the late Neoproterozoic volcano-sedimentary Guaratubinha Basin, southern Brazil. Journal of South American Earth Sciences, 80, 29-46. doi: https://doi.org/10.1016/j.jsames.2017.09.014

Basei, M. A. S., A. Nutman, O. Siga Jr, C. R. Passarelli, C. O. Drukas, 2009, The evolution and tectonic setting of the Luis Alves Microplate of Southeastern Brazil: an exotic terrane during the assembly of Western Gondwana. In: Gaucher, C.; Sial, A.N.; Halverson, G.P.; Frimmel, H.E. (Eds): Neoproterozoic-Cambrian Tectonics, Global Change and Evolution: a focus on southwestern Gondwana. Developments in Precambrian Geology, 16, Elsevier, pp. 273-291. doi: https://doi.org/10.1016/S0166-2635(09)01620-X

Besser, M. L., M. Brumatti, A. L. Spisila, 2021, Mapa geológico e de recursos minerais do estado do Paraná. Programa Geologia, Mineração e Transformação Mineral, Curitiba: CPRM, 1 mapa colorido, 235 x 90 cm. Escala: 1:600.000. url: https://rigeo.sgb.gov.br/handle/doc/22492

Bettú, D. F., 2004, Conectividade e Compartimentação dos Sistemas Aquíferos Caiuá e Serra Geral no Nordeste do Estado do Paraná. Dissertação (Mestrado em Geologia Exploratória). Departamento de

Geologia. Setor de Ciências da Terra, Universidade Federal do Paraná. Curitiba, PR, Brasil. url: https://hdl.handle.net/1884/2134

Blakely, R. J., R. W. Simpson, 1986, Approximating edges of source bodies from magnetic or gravity anomalies. Geophysics, vol. 51, pp. 1494-1498. doi: https://doi.org/10.1190/1.1442197

Bongiolo, A. B. S., 2011, Contribuição ao estudo da Bacia do Amazonas e seu embasamento através da magnetometria e gravimetria – PhD Thesis. Universidade Federal do Paraná, Curitiba, Paraná, Brasil. url: http://hdl.handle.net/1884/26906

Bongiolo, A. B. S., F. J. F. Ferreira, A. V. L. Bitterncourt, E. Salamuni, 2014, Connectivity and Magnetic-Structural Compartmentalization of the Serra Geral and Guarani Aquifer Systems in Central State of Paraná (Paraná Basin, Brazil) – Revista Brasileira de Geofísica, Vol. 32(1). doi: http://dx.doi.org/10.22564/rbgf.v32i1.402

Bongiolo, A. B. S., L. S. A. Szameitat, R.R. Severino, M. Brumatti, 2023, Aeromagnetic Map of the State of Paraná: An integration of aerial surveys executed in the state over the years. In: Eighteenth International Congress of the Brazilian Geophysical Society. Rio de Janeiro – RJ.

Briggs, I.C., 1974, Machine Contouring Using Minimum Curvature. Geophysics, v. 39, n. 1, p.39-48. doi: https://doi.org/10.1190/1.1440410

Brito Neves, B. B., M. C. Campos Neto, R. A. Fuck, 1999, From Rodinia to western Gondwana: an approach to the Brasiliano-Pan African cycle and orogenic collage. Episodes, Beijing, v. 22, p. 155-166. doi: https://doi.org/10.18814/epiiugs/1999/v22i3/002

Brumatti, M. A. L. Spisila, M. L. Besser, 2023, Mapa Geológico e de Recursos Minerais do Estado do Paraná – Escala 1:600.000. Curitiba: CPRM, status (unpublished; manuscript in preparation).

Campanha, G. A. C., G. R. Sadowski, 1999, Tectonics of the Southern Portion of the Ribeira Belt (Apiaí Domain). Precambrian Research, 98 (1): 31-51. doi: https://doi.org/10.1016/S0301-9268(99)00027-3

Campanha, G. A. C., F. M. Faleiros, M. A. S. Basei, C. C. G. Tassinari, A. P. Nutman, P. M. Vasconcelos, 2015, The Geochemistry and age of mafic rocks from the Votuverava Group, southern Ribeira Belt, Brazil: evidence for 1490 Ma oceanic back-arc magmatism. Precambriam Research, v. 266, p. 530-550. doi: https://doi.org/10.1016/j.precamres.2015.05.026

Castro, L. G., F. J. F. Ferreira, L. F. Cury, A. P. Fiori, P. C. Soares, A. P. Lopes, M. J. Oliveira, 2014, Interpretação qualitativa e semiquantitativa dos dados aeromagnéticos sobre a Zona de Cisalhamento Lancinha, porção meridional do Cinturão Ribeira no Estado do Paraná, Sul do Brasil. Geologia USP. Série Científica, 14(4), 3-18. doi: https://doi.org/10.5327/Z1519-874X201400040001

Castro, L. G., 2015, Arcabouço geofísico estrutural da porção meridional do Cinturão Ribeira e regiões adjacentes. PhD Thesis (Geologia Exploratória). Universidade Federal do Paraná, Curitiba, Paraná, Brazil. doi: http://hdl.handle.net/1884/37421

Cavalcante, F. L., C. A. Mendonça, U. S. Ofterdinger, O. A. De Souza Filho, 2020, Well productivity in the Ponta Grossa dike Swarm, Brazil: An integrated study with magnetic data inversion and clustering analysis of model solutions. Journal of Hydrology, 588, 125079. Doi: https://doi.org/10.1016/j.jhydrol.2020.125079

Cordani, U. G., V. A. Ramos, Fraga, L. M., M. Cegarra, I. Delgado, K. G. D. Souza, C. Schobbenhaus, 2016, Tectonic map of South America= Mapa tectónico de América del Sur= Mapa tectônico da América do Sul. url: https://rigeo.sgb.gov.br/handle/doc/16750

Cordell, L., V. Grauch, Mapping Basement magnetization zones from aeromagnetic data in the San Juan Basin, New México. In: W. Hinze (ed.) Utility of regional gravity and magnetic maps. SEG, P.181-197. 1985. doi: https://doi.org/10.1190/1.0931830346.ch16

Coutinho, J. M. V., 2008, Enxame de diques da junção tríplice do Paraná, Brasil meridional. Geologia USP. Série Científica 8.2 28-52. doi: https://doi.org/10.5327/Z1519-874X2008000200003

CPRM, 2019, Mapa magnetométrico do Brasil. Retrieved from:https://rigeo.sgb.gov.br/handle/doc/21299

Cury, L. F., O. Siga Junior, O. M. M. Harara, H. J. Prazeres Filho, M. A. S. Basei, 2008, Aspectos tectônicos das intrusões dos granitos Cerne, Passa Três e Rio Baixo, sudeste do Pré-cambriano Paranaense. Estudo baseado em datações Ar-Ar em micas. Geol. USP, Sér. Cient. São Paulo, 8(1): 87-104. doi: https://doi.org/10.5327/Z1519-874x2008000100007

Dentith M., S. Mudge, 2014, Gravity and magnetic methods. In: Geophysics for the mineral exploration geoscientist. Cambridge University Press. p. 85–192. doi: https://doi.org/10.1017/CBO9781139024358

Dragone, G. N., Bologna, M. S., Ussami, N., Gimenez, M. E., Alvarez, O., Klinger, F. G. L., Correa-Otto, S., 2021), Lithosphere of South American intracratonic basins: Electromagnetic and potential field data reveal cratons, terranes, and sutures. Tectonophysics, 811, 228884. doi: https://doi.org/10.1016/j.tecto.2021.228884

Evjen, H. M., 1936, The place of vertical gradient in gravitational interpretations. Geophysics, v. 1, p.27-136. doi: https://doi.org/10.1190/1.1437067

Faleiros, F. M., G. A. C. Campanha, L. Martins, S. R. F. Vlach, P. M. Vasconcelos, 2011, Ediacaran high-pressure colission metamorphism and tectonics of the southern Ribeira Belt (SE Brazil): Evidence for terrane accretion and dispersion during Gondwana assembly. Precambrian Research, 189(34):263-291.

doi: https://doi.org/10.1016/j.precamres.2011.07.013

Faleiros, F. M., S. M. Morais, V. S. Costa, 2012, Geologia e recursos minerais da folha Apiaí – SG.22-X-B-V, estados de São Paulo e Paraná, escala 1:100.000. São Paulo: CPRM. Programa Geologia do Brasil. url: https://rigeo.sgb.gov.br/handle/doc/11366

Faleiros, F. M., B. V. Ribeiro, G. A. D. C. Campanha, P. A. Cawood, D. I. G. Cabrita, M. T. A. G. Yogi, A. J. Forero-Ortega, 2022, Strain partitioning along terrane bounding and intraterrane shear zones: constraints from a long-lived transpressional system in West Gondwana (Ribeira Belt, Brazil). Lithosphere, 2021(Special 6), 2103213. doi: https://doi.org/10.2113/2022/2103213

Fernandes, L. A., C. M. M. Ribeiro, 2015. Evolution and paleoenvironment of the Bauru Basin (Upper Cretaceous, Brazil). Journal of South American Earth Sciences, 61: 71-90. doi: https://doi.org/10.1016/j.jsames.2014.11.007

Ferreira, F. J. F., R. A. V. Moraes, M. P. Ferrari, R. B. Vianna, 1981, Contribuição ao estudo do alinhamento estrutural de Guapiara. In: Simpósio Regional de Geologia, 3. Atas. Curitiba, SBG, Núcleo São Paulo, v.1, p. 226-240.

Ferreira, F. J. F., 1982a, Alinhamentos estruturais – magnéticos da região centro-oriental da Bacia do Paraná – reavaliação da potencialidade e prospectividade em hidrocarbonetos. Consórcio CESP-IPT, p.144-166.

Ferreira, F. J. F., 1982b, Integração de dados aeromagnéticos e geológicos: configuração e evolução tectônica do Arco de Ponta Grossa. Master's dissertation. Instituto de Geociências, Universidade de São Paulo (USP). São Paulo, SP, Brazil. doi: https://doi.org/10.11606/D.44.1983.tde-14082013-161535

Ferreira, F. J. F., C. V. Portela Filho, E. F. Rosa Filho, S. P. Rostirolla, 2004, Connection of the Serra Geral and Guarani Aquifer Systems across Ponta Grossa Arch (Paraná Basin, Brazil). In: XXXIII Internacional Congress of the International Association of Hydrogeologists (IAH) and 7 International Congress of the Latin-American Association of Underground Hydrology for Development (ALHSUD). Zacatecas, México (CD ROM).

Ferreira, F. J. F., C. V. Portela Filho, E. F. Rosa Filho, S. P. Rostirolla, 2005, Conectividade e compartimentação dos sistemas aquíferos Serra Geral e Guarani na região central do Arco de Ponta Grossa (Bacia do Paraná, Brasil). Revista Latino Americana de Hidrogeologia, v.5 p.61-74. url: https://hdl.handle.net/1884/2134

Ferreira F. J. F., J. Souza, A. B. S. Bongiolo, L. G. Castro, M. A. T. Romeiro, 2010, Realce do gradiente horizontal total de anomalias magnéticas usando a inclinação do sinal analítico. Parte I: Aplicação a dados sintéticos. In: IV Simpósio Brasileiro de Geofísica, SBGf. Brasília, Anais, p. 1-6.

Ferreira F. J. F., J. Souza, A. B. S. Bongiolo, L. G. Castro, 2013, Enhancement of the total horizontal gradient of magnetic anomalies using tilt angle. Geophysics, vol. 78, issue 3, pp. J33-J41. doi: https://doi.org/10.1190/geo2011-0441.1

Gunn, P. J., 1975. Linear Transformations of Gravity and Magnetics Fields. Geophysical Prospecting, n. 23. p 300-312. doi: https://doi.org/10.1111/j.1365-2478.1975.tb01530.x

Gunn, P. J., P. R. Milligan, 1997a, Enhancement and presentation of airborne geophysical data. AGSO Journal of Australian Geology & Geophysics, v. 17, n. 2, p. 63-75. url: https://pid.geoscience.gov.au/dataset/ga/81493

Gunn, P. J., 1997b, Quantitative methods for interpreting aeromagnetic data: a subjective review. AGSO Journal of Australian Geology & Geophysics, v. 17, n. 2, p. 105-113. url: https://pid.geoscience.gov.au/dataset/ga/81496

Harara, O. M. M., 2001, Mapeamento e investigação petrológica e geocronológica dos litotipos da região do alto Rio Negro (PR-SC): um exemplo de sucessivas e distintas atividades magmáticas durante o Neoproterozoico III. PhD Thesis. Instituto de Geociências, Universidade de São Paulo, São Paulo, SP, Brasil. doi: https://doi.org/10.11606/T.44.2001.tde-17112015-091642

Hartmann, L. A., J. O. Santos, N. E. A. L. McNaughton, M. A. Vasconcellos, L. C. Da Silva, 2000, Ion microprobe (SHRIMP) dates complex granulite from Santa Catarina, southern Brazil. Anais da Academia Brasileira de Ciências, 72, 559-572. doi: https://doi.org/10.1590/S0001-37652000000400007

Heilbron, M., W. U. Mohriak, C. M. Valeriano, E. J. Milani, J. Almeida, M. Tupinambá, 2000, From collision to extension: the roots of the southeastern continental margin of Brazil. Geophysical Monograph-American Geophysical Union, v. 115, p. 1-32.

Heilbron, M., A. C. Pedrosa-Soares, M. D. C. Campos Neto, L. D. Silva, R. A. J. Trouw, V. D. A. Janasi, 2004, Província Mantiqueira. In Geologia do continente Sul-americano: evolução da obra de Fernando Flávio Marques de Almeida, 203-235.

LaFehr, T. R. & M. N. Nabighian, 2012, Fundamentals of gravity exploration. Society of Exploration Geophysicists, 232 p.

Li, X., 2006, Understanding 3D analytic signal amplitude: Geophysics,71, 2, L13–L16. doi: https://doi.org/10.1190/1.2184367

Licht, O. A. B., E. E. Arioli, 2018, Mapeamento geológico do Grupo Serra Geral no Estado do Paraná. Nota Explicativa. ITCG, Curitiba, PR, Brasil.

Maack, R., 1968, Geografia Física do Estado do Paraná. 350 p.

Marques, A., O. A. Zanotto, A. B. França, M. A. M. Astolfi, O. B. Paula, 1993, Compartimentação tectônica da bacia do Paraná. Petrobras – Núcleo de Exploração da Bacia do Paraná, Curitiba, 87 p.

Mantovani, M. S. M., M. C. L. Quintas, W. Shukowsky, B. B. Brito Neves, 2005, Delimitation of the Paranapanema Proterozoicblock: A geophysical contribution. Episodes, vol.28, no 1. doi: https://doi.org/10.18814/epiiugs/2005/v28i1/002

Milani, E. J., 1997, Evolução tectono-estratigráfica da Bacia do Paraná e seu relacionamento com a geodinâmica fanerozóica do Gondwana sul-ocidental. 255 p. PhD Thesis. Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brasil.

Milani, E. J., V. A. Ramos, 1998, Orogenias paleozóicas no domínio sul-ocidental do Gondwana e os ciclos de subsidência da Bacia do Paraná. Revista Brasileira de Geociências, 28(4), 473-484. doi:10.25249/0375-7536.1998473484

Milani, E. J., 2004, Comentário sobre a origem e a evolução tectônica da Bacia do Paraná. In: Mantesso-Neto, V.; Bartorelli, A; Carneiro, C. D. R.; Brito Neves, B. B. de (org.). Geologia do continente Sul-americano: Evolução das obras das obras de Fernando Flávio Marques de Almeida. Editora Beca. São Paulo – SP. p. 265-279.

Milani, E. J., J. Henrique, G. Melo, P. A. Souza, L. A. Fernandes, A. B. França, 2007, Bacia do Paraná. Boletim de Geociências da Petrobras,15: p. 265-287.

Miller, H. G., V. Singh, 1994b, Potential field tilt – a new concept for location of potential field sources. Journal of Applied Geophysics, v. 32, p.213-217. doi: https://doi.org/10.1016/0926-9851(94)90022-1

MINEROPAR Serviço Geológico do Paraná, 2001, Atlas geológico do Estado do Paraná. v. 1. Governo do Estado do Paraná. Curitiba, PR, Brasil.

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, 507–517. doi: https://doi.org/10.1190/1.1440276

Padilha, A. L., Vitorello, Í., Antunes, C. E., Pádua, M. B., 2015, Imaging three-dimensional crustal conductivity structures reflecting continental flood basalt effects hidden beneath thick intracratonic sedimentary basin. Journal of Geophysical Research: Solid Earth, 120(7), 4702-4719. doi: https://doi.org/10.1002/2014JB011657

Paine, J., M. Haederle, M. Flis, 2001, Using transformed TMI data to invert for remanently magnetized bodies: Exploration Geophysics, 32, 238–242. doi: https://doi.org/10.1071/EG01238

Passarelli, C. R., M. A. S. Basei, K. Wemmer, O. Siga Junior, P. Oyhantçabal, 2011, Major shear zones of southern Brazil and Uruguay: escape tectonics in the eastern border of Rio de La Plata and Paranapanema cratons during the Western Gondwana amalgamation. International Journal of Earth Sciences, 100(2), 391-414. doi: https://doi.org/10.1007/s00531-010-0594-2

Passarelli, C. R., M. A. S. Basei, K. Wemmer, O. Siga Junior, O. M. M. Harara, 2018, The Luis Alves and Curitiba Terranes: Continental Fragments in the Adamastor Ocean. In: Siegesmund, S., Basei, M., Oyhantçabal, P., Oriolo, S. (eds) Geology of Southwest Gondwana. Regional Geology Reviews. Springer, Cham. doi: https://doi.org/10.1007/978-3-319-68920-3_8

Pinheiro, M. R., P. Cianfarra, 2021, Brittle Deformation in the Neoproterozoic Basement of Southeast Brazil: Traces of Intraplate Cenozoic Tectonics. Geosciences, 11(7), 270. doi: https://doi.org/10.3390/geosciences11070270

Portela Filho C.V., 2003, Condicionamento estrutural magnético do Sistema Aquífero Serra Geral na região central do Arco de Ponta Grossa (Bacia do Paraná) e sua conectividade com o Sistema Aquífero Guarani. Dissertação de Mestrado, Programa de Pós-Graduação em Geologia Exploratória, Universidade Federal do Paraná, Curitiba, PR, Brasil. url: https://hdl.handle.net/1884/48618

Prazeres Filho, H. J., 2000, Litogeoquímica, geocronologia (U-Pb) e geologia isotópica dos complexos graníticos Cunhaporanga e Três Córregos, estado do Paraná. Master's thesis. Instituto de Geociências, Universidade de São Paulo, São Paulo, SP, Brasil. doi: https://doi.org/10.11606/D.44.2000.tde-28092015-155909

Reis Neto, J.M., 1994, Faixa Itaiacoca: registro de uma colisão entre dois blocos continentais no Neoproterozoico. PhD Thesis Instituto de Geociências, Universidade de São Paulo, São Paulo, SP, Brasil. doi: https://doi.org/10.11606/T.44.1994.tde-30062015-150033

Renne, P. R., K. Deckart, M. Ernesto, G. Fe, E. M. Piccirillo, 1996, Age of the Ponta Grossa dike swarm (Brazil), and implications to Paraná flood volcanism. Earth and Planetary Science Letters, 144(1-2), 199-211. doi: https://doi.org/10.1016/0012-821X(96)00155-0

Riccomini C. O., 1989, Rift Continental do Sudeste do Brasil. PhD Thesis Instituto de Geociências, Universidade de São Paulo, São Paulo, SP, Brasil. doi: https://doi.org/10.11606/T.44.1990.tde-18032013-105507

Roest, W. R., V. Verhoef, and M. Pilkington, 1992, Magnetic interpretation using the 3-D analytic signal: Geophysics, 57, 116–125. doi: https://doi.org/10.1190/1.1443174

Santos, L. R., R. Leandro, G. Fedalto, A. L.; Spisila, A. M. Bahniuk, O. Siga Jr, L. F. Cury, 2021, The Capiru Group: from passive margin to syn-orogenic units, implications for the evolution of the northen margin of the Curitiba microplate, Western Gondwana. Journal of South American Earth Sciences, v. 112. doi: https://doi.org/10.1016/j.jsames.2021.103555

Siga Jr, O., M. A. S. Basei, A. Machiavell, ,1993, Evolução geotectônica da porção NE de Santa Catarina e SE do Paraná, com base em interpretações geocronológicas. Brazilian Journal of Geology, 23(3), 215-223. doi: https://doi.org/10.25249/0375-7536.1993233215223

Siga Jr., O., M. A. S. Basei, J. M. Reis Neto, A. Machiavelli, O. M. M. Harara, 1995, O complexo Atuba: um cinturão Paleoproterozoico intensamente retrabalhado no Neoproterozoico. Geol. USP, Sér. cient. São Paulo, v. 26, p. 69-98. doi: https://doi.org/10.11606/issn.2316-8986.v26i0p69-98

Siga Jr, O., M. A. S. Basei, K. Sato, H. J. Prazeres Filho, L. F. Cury, W. Weber, C. R. Passarelli, O. M. M. Harara, J. M. Reis Neto, 2003, U-Pb (zircon) ages of metavolcanic rocks from the Itaiacoca Group: tectonic implications. Geol. USP, Sér. Cient. São Paulo, v. 3, p. 39-49. doi: https://doi.org/10.5327/S1519-874X2003000100004

Silva, J. B. C., 1996, 2-D magnetic interpretation using the vertical integral. Geophysics, 61, 387–393. doi: https://doi.org/10.1190/1.1443967

Silva, A. B., 2007, Conectividade e compartimentação magnética-estrutural dos sistemas aquíferos Serra Geral e Guarani na região central do estado do Paraná. Master's thesis. Universidade Federal do Paraná, Curitiba, PR, Brasil. url: http://hdl.handle.net/1884/13903

Simões Neto, J. A., F. J. F. Ferreira, A. B. Silva, 2007, Processamento de dados aeromagnéticos da região central do estado do Paraná. 15º EVINCI, Universidade Federal do Paraná, Curitiba. p.252.

Soares, P. C., P. E. Barcellos, S. M. Csordas, J. T. Mattos, M. G. Balieiro, P. R. Meneses, 1982, Lineamentos em imagens Landsat e Radar e suas implicações no conhecimento tectônico da Bacia do Paraná. II Simpósio de Sensoriamento Remoto, CNPq-INPE, Brasília.

Soares, A. P., P. C. Soares, D. F. Bettú, M. Holz, 2007, Compartimentação Estrutural da Bacia do Paraná: A questão dos lineamentos e sua influência na distribuição do sistema aquífero Guarani – Geociências, v.26, m. 4 p. 297-311.

Souza, A. P., 1990, Mapa geológico na escala 1:50.000 e esboço de evolução tectônica e sedimentar do grupo Itaiacoca, nas folhas Barra do Chapéu e Ouro Verde (SP-PR). Master's thesis – Instituto de Geociências, Universidade de São Paulo, São Paulo, SP, Brasil. doi: https://doi.org/10.11606/D.44.1990.tde-21082015-130642

Souza Filho, O. A., L. S. A. Szameitat, 2022, Contribuição aos estudos geofísicos da Bacias Interiores-Bacia do Paraná. In: REATE2020 - SCT3. Avaliação do potencial de geração de hidrocarbonetos em áreas de bacias sedimentares terrestres. [S.l.]: ENEP 156p. Relatório Subcomitê Potencial de Petróleo e Gás Onshore. Retrieved from https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-696/REATE2020_Relatorio_final_SC3_Potencial%20de%20Gera%C3%A7%C3%A3o_v1_23set22.pdf

Souza, J., S. P. Oliveira, L. S. A. Szameitat, O. A. de Souza Filho, F. J. F. Ferreira, 2023. Fourier domain vertical derivative of the non-potential squared analytical signal of dike and step magnetic anomalies: a case of serendipity. Geophysics, 89(2), 1-48. doi: https://doi.org/10.1190/geo2022-0760.1

Vilalva, F. C. J., A. Simonetti, S. R. F. Vlach, 2019, Insights on the origin of the Graciosa A-type granites and syenites (Southern Brazil) from zircon U-Pb geochronology, chemistry, and Hf and O isotope compositions. Lithos, v. 340341, p. 20-33. doi: https://doi.org/10.1016/j.lithos.2019.05.001

Zalán, P. V., S. Wolff, J. C. J. Conceição, M. A. M. Astolf, I. S. Vieira, V. T. Appi, O. Zanotto, 1987, A. Tectônica e Sedimentação da Bacia do Paraná. In: Simpósio Sul-Brasileiro De Geologia, III, Curitiba: Sociedade Brasileira de Geologia, v.1, p. 441-473.

Zalán, P. V., S. Wolff, J. C. J. Conceição, M. A. M. Astolf, I. S. Vieira, V. T. Appi, E. V. S. Neto, J. R. Cerqueira, A. Marques, 1990, The Paraná Basin, Brazil. In: Interior cratonic Basins, Leighton et al. (coords). AAPG Memoir, n. 51; p. 681-708.

Zalán, P. V., 2004, Evolução fanerozóica das bacias sedimentares brasileiras. In: Mantesso-Neto, V.; Bartorelli, A.; Carneiro, C.D.R.; Brito-Neves, B.B. Geologia do Continente Sul-Americano: Evolução da obra de Fernando Flávio Marques de Almeida. p. 595-612.

Bongiolo, A.B.S: conceptualization, field data colect, processing, interpretations and all reviews, writing-original draft preparation, review and editing, supervision; **Szameitat, L.S.A**: field data colection, field data leveling, processing, interpretations and all reviews, writing-original draft preparation, review and editing; **Severino, R.R.**: interpretation, review and editing; **Brumatti, M.**: writing – review; **Spisila, A.L.**: writing draft of regional data and review; **Ferreira, F.J.F.**: review and editing; **Baldessar Netto, P.**: data processing; **Pereira, E.K.C.:** data processing, review and editing.