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

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ABSTRACT. Over the last decades, several aerial survey campaigns have been conducted in the State of Paraná. However, we have not had 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 integrating the data, we applied processing techniques on public airborne magnetic data, available from the Geological Survey of Brazil database (GeoSGB). For this integration, the minimum curvature interpolation was used with cell sizes according to each survey. All gridded data were 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 its basement and comparing them with the most important structures already mapped in surface over the years. All the data present in this work and other filter tests are available and can be accessed in the supplementary material (https://acervodigital.ufpr.br, https://hdl.handle.net/1884/89075 and also at the 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 large-scale outcropping geological features. In the last decades, efforts have been done for obtaining geophysical data in the Paraná State area, in order to get a compre-

hensive view of the subsurface geological setting. For previous studies, we can cite the work of Simões Neto et al. (2007), who made the (partial) Phanerozoic Magnetic Map of the state. The data were later supplemented with geophysical work on the Paraná Basin from the REATE Program Program for the Revitalization of Oil and Natural Gas Exploration and Production Activity in Land Areas (Souza Filho and 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; Souza Filho and Szameitat, 2022; Santos et al., 2021). 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 data integration and realize a general analysis to build the Integrated Aeromagnetic Map of the Paraná State using the previous public data available from 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. 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 indicate aquifer recharge and discharge zones. The dyke swarm of the Ponta Grossa Arch is of great importance in the region because, besides being very thick and extensive, it has 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 amalga-

mation 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 and 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., 2011). 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 and 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 with the Atlantic opening, in which it is linked with other dyke complexes; also, it 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 the NW-SE regional orientation of brittle basement structures, which are pervasive in the Paraná Basin (NW oriented structures; Figure 2). For example, the NW-SE central area of the PGDS is inherited at least since the Devonian (Pinto and Vidotti,

2019; Souza Filho and Szameitat, 2022). Dykes of PGDS have concentrated occurrence around 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, the close relation, governmental efforts have been made to improve 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 the Angolan Craton led to 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. The Paranapanema Block is a continental segment, which may have acted as a paleoplate in the Brazilian orogenic cycle. Several works have 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 and 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 with post-orogenic transcurrent movements, which may have been active up to the Cenozoic (Pinheiro and Cianfarra, 2021; Santos et al., 2021). The approximately E-W oriented faults are in agreement with the regional neotectonic stress-field (Pinheiro and Cianfarra, 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 Serviço Geológico do Paraná, 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 with 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 and Ramos, 1998). The Paraná Basin borders are mostly erosive, associated with 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 the 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., 2021), 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 in Figure 2), whose 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 with the Caiuá desertic environment (Fernandes and Ribeiro, 2015).

METHODS

Airborne Magnetic Data

Filtering methods are commonly applied to data of potential field 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 and Mudge, 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 to
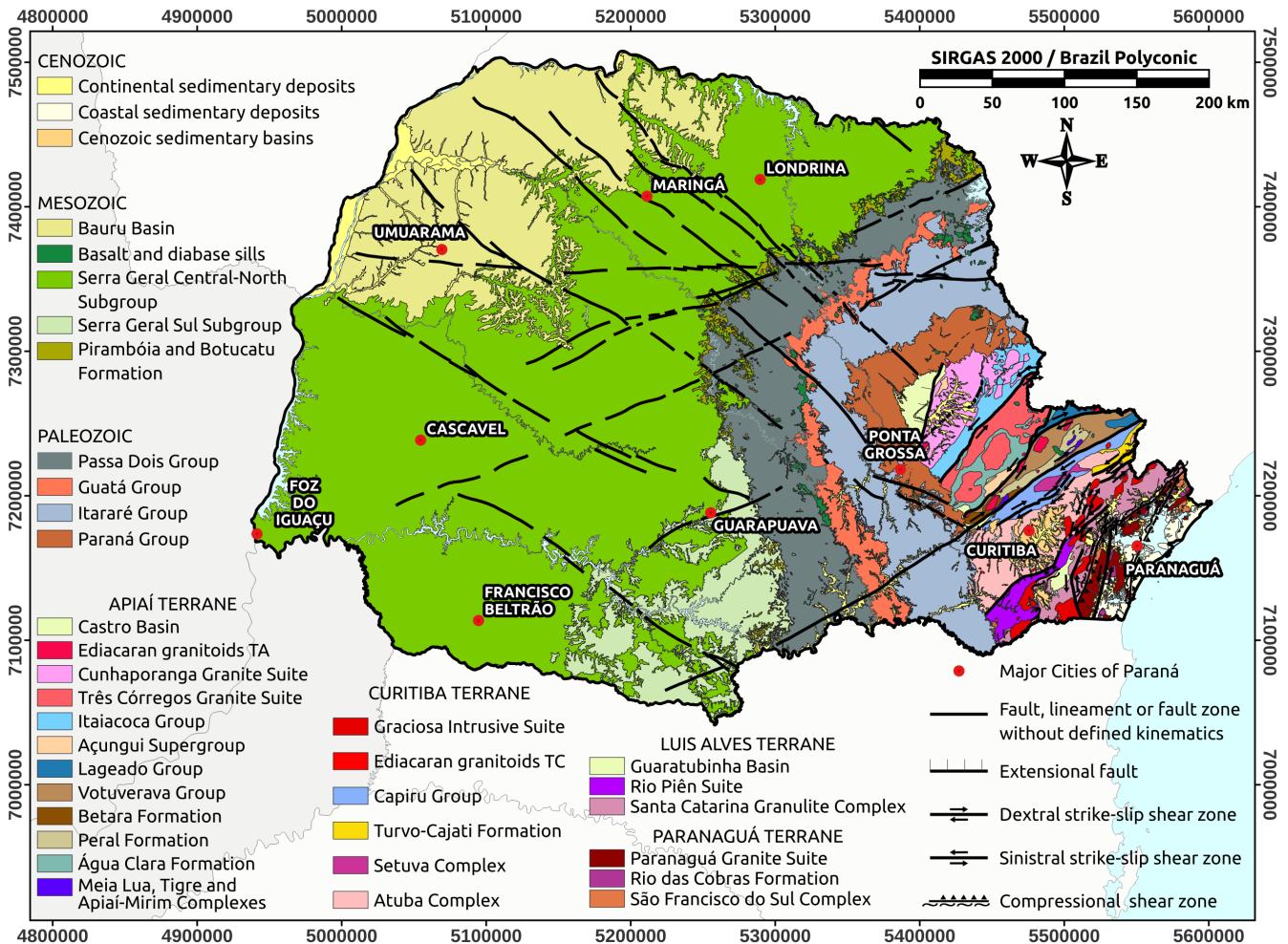
Figure 1: Simplified Geological Map of the Paraná State (adapted from Besser et al., 2021).

perform 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 were not suitable for merging with other grids, due to mathematical artifacts or high noise. In these cases, we tested larger space values. In the Rio Ivaí and Botucatu areas, the adjusted cell size was $\frac{1}{4}$ 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 taking into account the Nyquist theorem (e.g., LaFehr and Nabighian 2012). Since the highest survey (0001_Bacia_do_Parana_28058) has 1800 m of nominal altitude, all of the gridded data were transformed by the upward continuation filter (up to 1800 m) prior to the grid merging. The interpolated datasets were integrated following the sequence presented 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 integrating all the surveys. Since most of the applied filters are based on derivatives, which enhances the high frequency noise, we opted to continue 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).
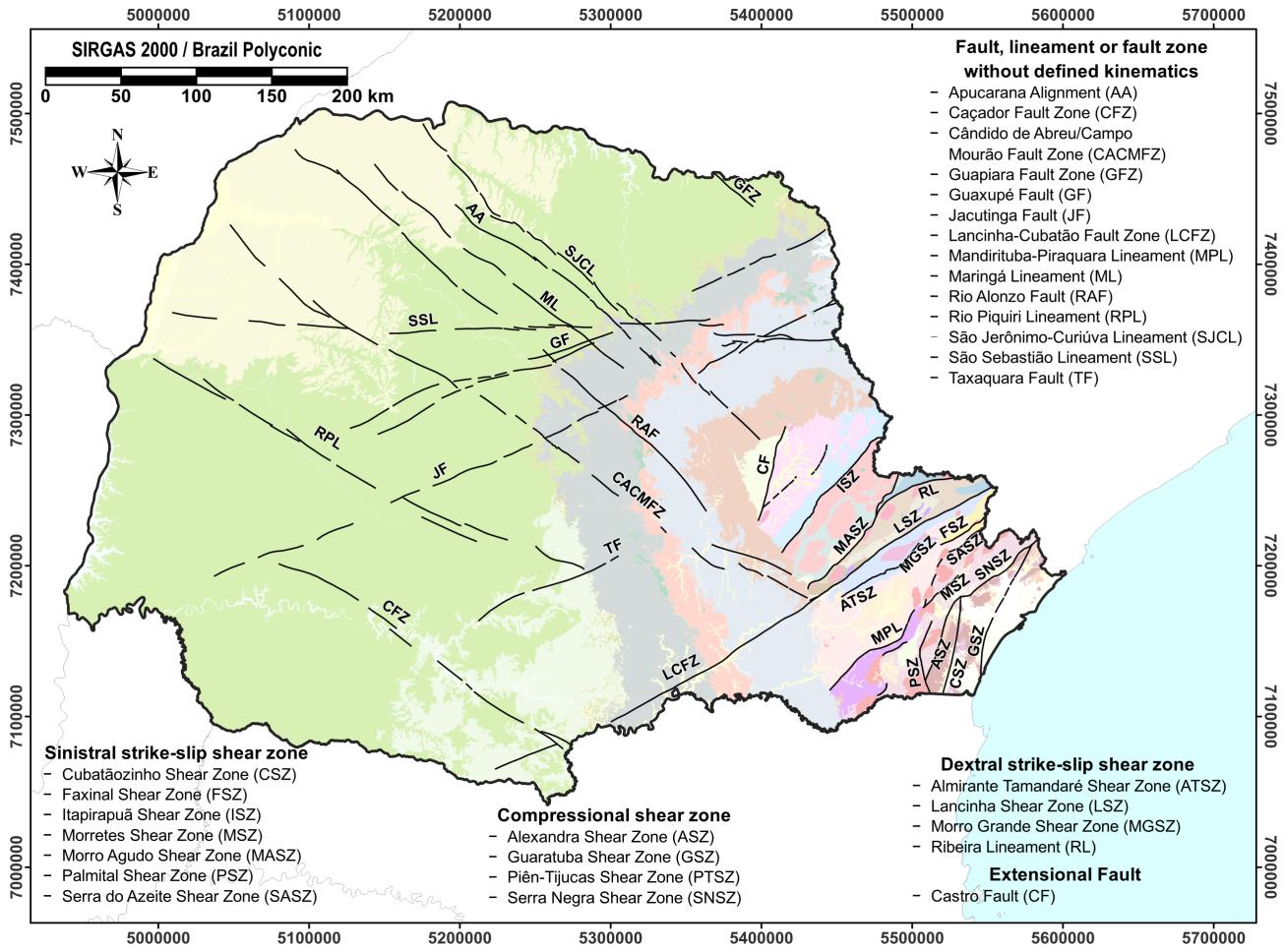
Figure 2: Structural framework of Paraná State (adapted from Besser et al., 2021).

Upward continuations

As is well known, the upward continuation procedure (Gunn, 1975) 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 were at different altitudes.

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

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.

$$VDR = \frac{\partial \Delta T}{\partial z} = \lim_{\Delta z \to 0} \frac{\Delta T(x,y,z) - \Delta T(x,y,z-\Delta z)}{\Delta z}, \qquad (2)$$

Total Horizontal Derivative (THDR)

The calculation of the horizontal derivative of the magnetic or gravimetric field (THDR; Cordell and 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.

$$THDR(x,y) = \left[\left(\frac{\partial g_z(x,y)}{\partial x}\right)^2 + \left(\frac{\partial g_z(x,y)}{\partial y}\right)^2\right]^{1/2}, \qquad (3)$$

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 to mitigate mathematical artifacts.

No.	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.

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; Gunn and Milligan, 1997), 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.

$$\left| A_{(x,y,z)} \right| = \sqrt{\left(\frac{\partial \Delta T}{\partial x} \right)^2 + \left(\frac{\partial \Delta T}{\partial y} \right)^2 + \left(\frac{\partial \Delta T}{\partial z} \right)^2}, \tag{4}$$

Tilt Derivative (TDR)

The tilt derivative (TDR; Miller and 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.

$$TDR = tan^{-1} \left(\frac{\partial \Delta T}{THDR} \right), \tag{5}$$

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). It is recommended for mapping mineral exploration structures
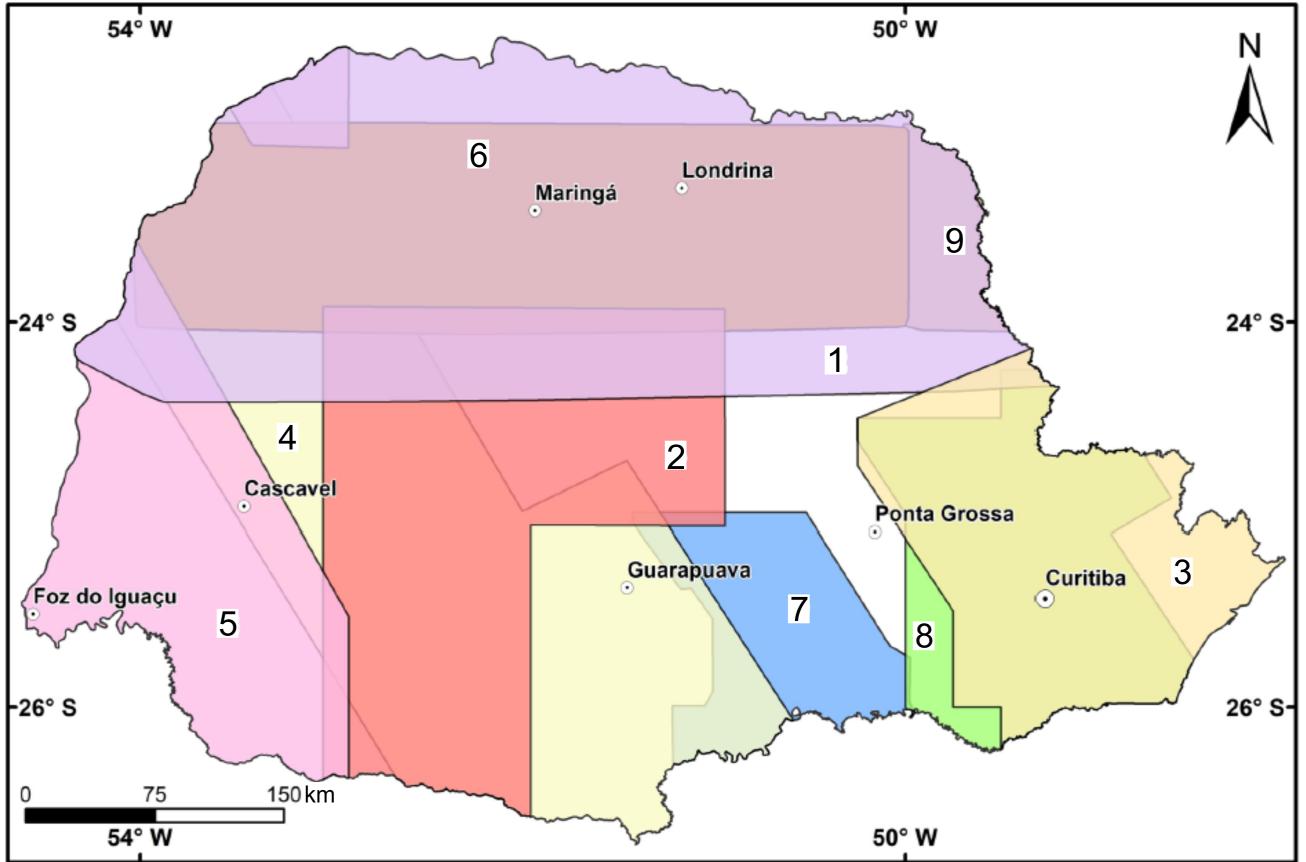
Figure 3: Location map of the surveys listed in Table 1.

and targets, and it 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.

$$\text{TAHG} = \tan^{-1}\left(\frac{\frac{\partial \text{THDR}}{\partial z}}{\sqrt{\left(\frac{\partial \text{THDR}}{\partial x}\right)^2 + \left(\frac{\partial \text{THDR}}{\partial y}\right)^2}}\right),$$
(6)

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. (2023) 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.

$$VIAS = \int_0^\infty \sqrt{\left(\frac{\partial \Delta T}{\partial x}\right)^2 + \left(\frac{\partial \Delta T}{\partial y}\right)^2 + \left(\frac{\partial \Delta T}{\partial z}\right)^2},$$
(7)

Automated and manual tracking of magnetic features

Blakely and 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 with a manual tracing of lineaments, focusing on possible faults and large textural domains.

RESULTS AND DISCUSSION

Magnetic maps

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 - Serviço Geológico do Brasil, 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, was 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 were the upward continued data (Figure 6). Figure 7 represents 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.

Geological-Geophysical Integration

Figure 8c illustrates manual interpretation based mainly 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 et al. (1981); Ferreira (1982a,b); Soares et al. (1982, 2007); Zalán et al. (1987, 1990); Milani (2004); Simões Neto et al. (2007); and Souza Filho and Szameitat (2022). In general, there was a good spatial correlation between the geological and geophysical features, with some variations among those authors. In this project, the geological significance of the magnetic domains was due to the 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 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, 1982a; Pinto and Vidotti, 2019), even after the emplacement of the dyke swarm (Licht and Arioli, 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 the 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 and 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 central-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 on 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).

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 having significant loss of high frequency; also, the smoothed anomalous grid represents deep structures or shallow structures that persist 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 subvertical dipping. Despite those limitations, the obtained magnetic maps agree with the aiming of this project, which intends to provide accessible datasets for the geological community and an integrated view of magnetic geological structures.
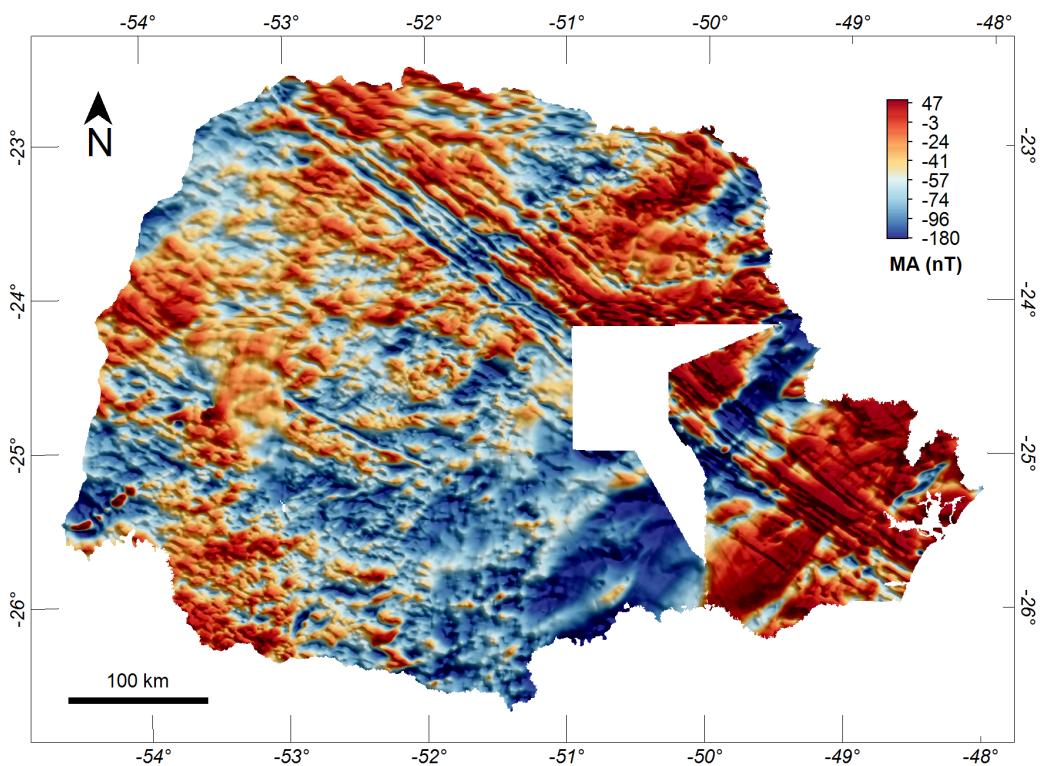
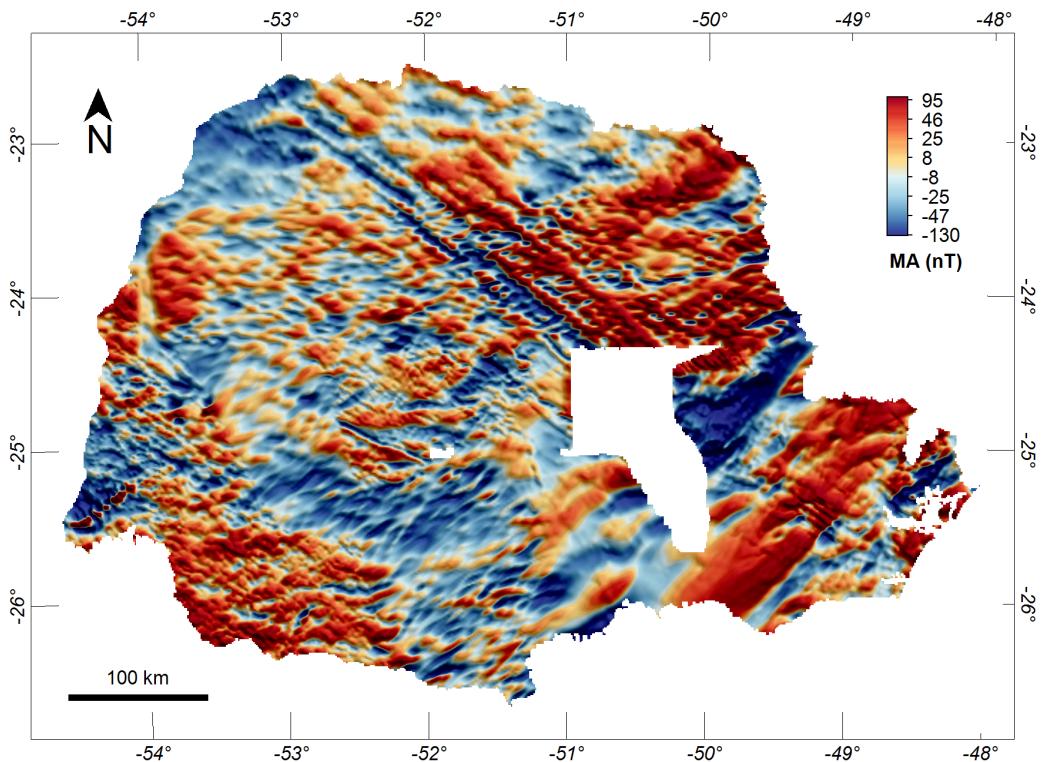Figure 4: Integrated magnetic anomaly map.

Figure 5: Map of magnetic anomaly from previous compilation (CPRM - Serviço Geológico do Brasil, 2019).
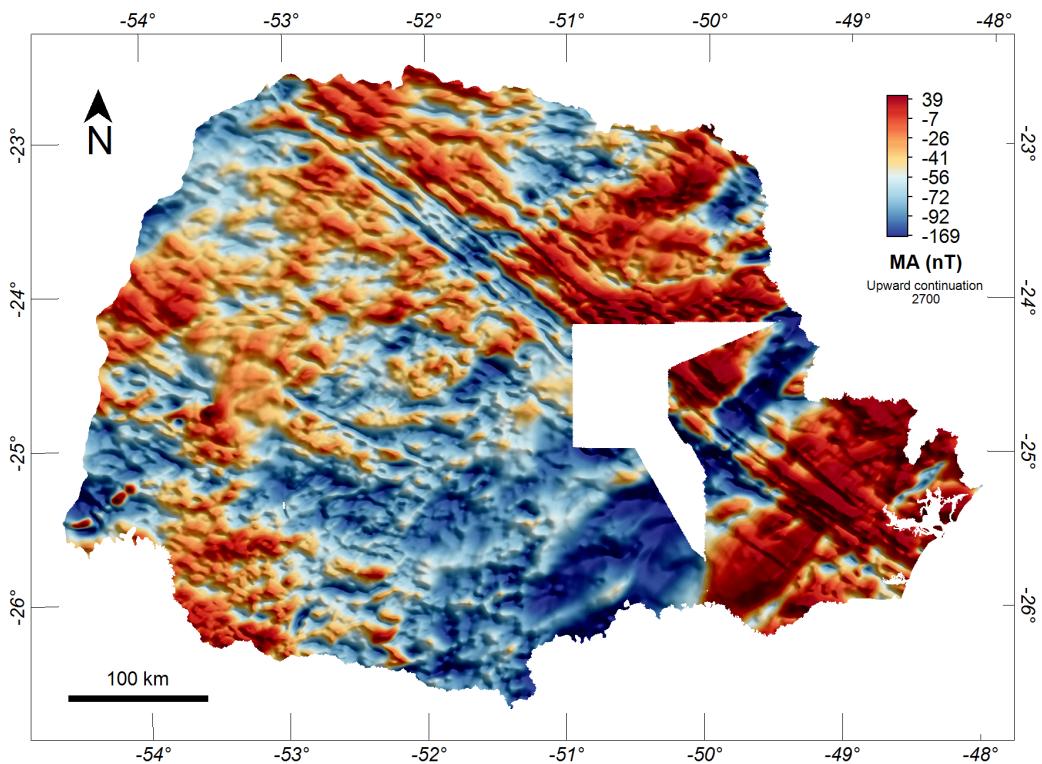
Figure 6: Map of magnetic anomaly upward continued to 2700 m.

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 up 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 lateral continuity of magnetic anomalies, in relation to previous data integration (CPRM - Serviço Geológico do Brasil, 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 are available at the Universidade Federal do Paraná - UFPR scientific repository https://acervodigital.ufpr.br, https://hdl.handle.net/1884/89075 and also at the Zenodo open-access research repository https://doi.org/10.5281/zenodo.12820642.
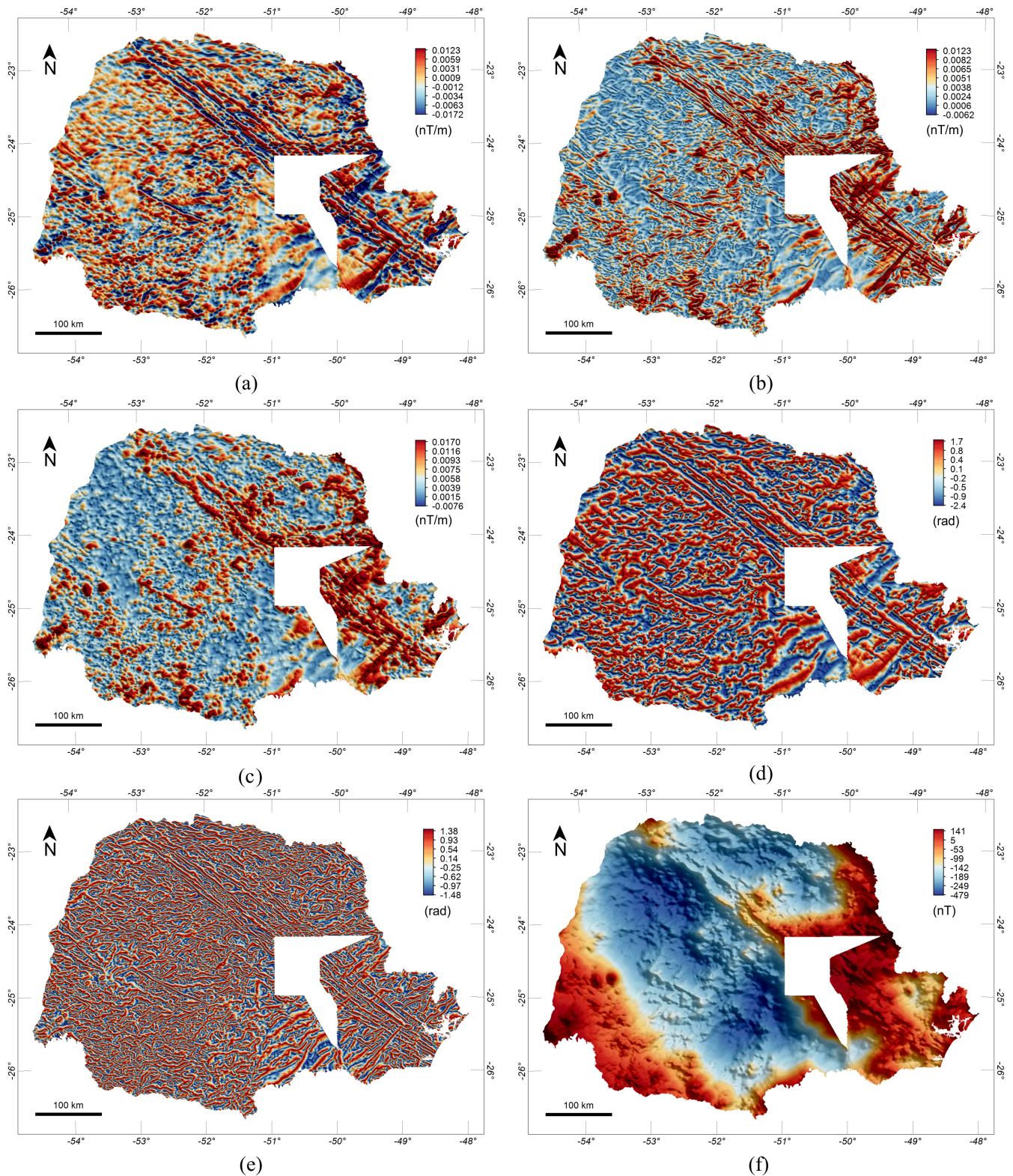
Figure 7: Magnetic maps obtained using the vertical derivative (a), the total horizontal derivative (b), the analytical signal (c), the tilt derivative (d), the tilt angle of the horizontal derivative (e) and the vertical integral of the analytical signal (f) in the Paraná State.

Fault/Fault zone/Lineament/Arch axis

C - Castro Fault
CA - Campo Mourão-Cândido de Abreu Fault Zone
Cç - Caçador Fault Zone
G - Guaxupé Fault Zone
GL - Guapiara Lineament
IT - Itapirapuã Fault Zone
J - Jacutinga Fault Zone
L - Lancinha-Cubatão Fault Zone
MA - Morro Agudo
MP - Mandiruba-Piraquara Fault Zone
PG - Ponta Grossa Arch
R - Ribeira Fault Zone
RP - Rio Piquiri Lineament
SS - São Sebastião Lineament
T - Taxaquara Fault

Outcropping and inferred basement geology

— Shallow geological structure
--- Magnetic lineament (faults and structural lineaments)
·-·- Magnetic lineament - possible lateral continuation of outcropping structures or related fault
— Magnetic lineament match   outcropping structure
▓ Ponta Grossa Dyke Swarm
■ Apiaí Terrane - prevalence of high positive anomaly (SE) and low magnetic values (NW)
■ Curitiba Terrane - high positive anomaly
■ Paranaguá Terrane - high positive anomaly
■ Undifferentiated domain - prevalence of low magnetic values
■ Hidden orogenic trend (?) - relative high magnetic values and high frequency anomalies
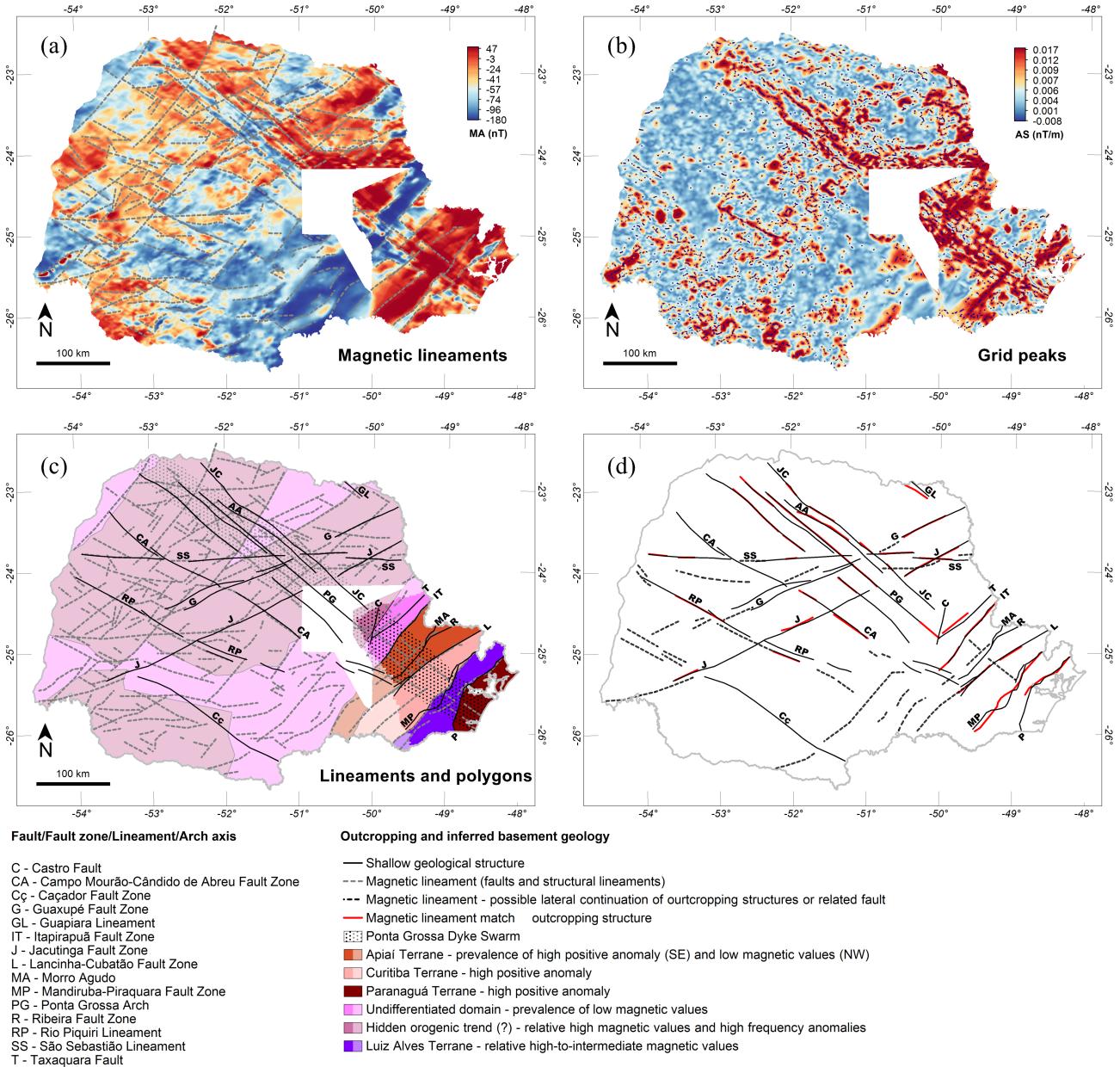■ Luiz Alves Terrane - relative high-to-intermediate magnetic values

Figure 8: Map of magnetic anomalies 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 out-cropping 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.

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