Journal of the Geological Survey of Brazil vol 6, n2, 193-215, August 2023

Journal of the Geological Survey of Brazil

Geophysical and geological framework of the southern edge of the Parnaíba Basin, NE Brazil

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Abstract

The application of geophysical techniques to highlight and characterize magnetic and gravity anomalies was carried out along a research area at the southern edge of the Parnaíba Basin. This study was conducted through qualitative and quantitative interpretations of magnetic and gravity data, supported by surface geological information, reflection seismic data, stratigraphic well data, field data, and magnetic susceptibility and density measurements of rock samples collected in outcrops. The study used the 3D magnetization vector inversion method, and 4 regional transects were performed for 2.5D modeling of magnetic and gravity data. The investigation revealed the configuration of the structural framework of the southern edge of the Parnaíba Basin. The characterization of magnetic anomalies allowed the definition of four main domains. Three magnetic zones were fragmented by depth, in the intervals of 20 km to 30 km, 5 km to 8 km and 0.5 km to 1 km, which demonstrate the association of magnetic anomalies with shallow and deep crustal structures. The magnetic susceptibility data show good correlation with the main structural discontinuities, and in particular with the Transbrasilian Zone. The results show that the maximum thickness of the sedimentary cover in the basin is approximately 2 km. No features associated with grabens or rifts were identified along the transects, and the presence of gravity and pseudo-gravity lows are closely related to less dense lithological units of the upper crust, such as granitic masses and supracrustal sequences. The reactivations of the Transbrasilian Zone during the Mesozoic generated deep structures in the crust that promoted the rise of basaltic rocks and the intrusion of kimberlitic bodies.

Article Information

Publication type: Research Papers
Received 20 April 2023
Accepted 14 July 2023
Online pub. 21 July 2023
Editor: David Castro

Keywords:
Parnaíba Basin
Tectonic framework
Potential geophysical methods
Reflection seismic
Geophysical modeling
Geophysical inversion

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1. Introduction

Over the last few years, several works have used different methods to try to better understand the configuration of the tectonic framework of the Parnaíba Basin (Brito Neves et al. 1984; Cunha 1986; Góes et al. 1990; Cordani et al. 2009; Daly et al. 2018; De Castro et al. 2014; Tozer et al. 2017; Soares et al. 2018; Porto et al. 2022). This understanding is extremely importance in view of the potential for energy mineral resources that the basin offers. In fact, most studies involving this theme are concentrated in the most central portion of the basin, due to the location of the main depocenters and hydrocarbon accumulations. However, studies carried out at the edges of sedimentary basins are increasingly important and directly reveal the contact relationships with the basement rocks (Pedrosa Jr. et al. 2017; Lima and Jardim de Sá 2017; Romero et al. 2019; Santos et al. 2018; Queiroz 2019; Rocha et al. 2019; Cerri et al. 2020; Romero-Beltran et al. 2022).

The formation of intracratonic basins, as is the case of the Parnaíba Basin, is a reflection of a series of geodynamic processes initiated at the end of the Neoproterozoic. The construction of Occidental Gondwana (Figure 1) involved the closure of oceanic basins, the joining of cratonic cores and the attachment of accretionary complexes along mobile belts (Dalziel 1997; Cordani et al. 2013; Brito Neves and Fuck 2014; Caxito et al. 2021; Porto et al. 2022).

Porto et al. (2022) carried out an extensive compilation of geophysical and geological data in order to determine the configuration of the tectonic framework of the Parnaíba Basin and adjacent regions. According to these authors, according to the interpretation of the geodynamic evolution along the western portion of Gondwana proposed by Caxito et al. (2021), the Parnaíba Basin is embedded between the Amazonian-West African and Central African crustal megablocks (AWB and CAB, Figure 1). Throughout the extension of the Parnaíba Basin, there is the extension of several geological

ISSN: 2595-1939
https://doi.org/10.29396/jgsb.2023.v6.n2.3
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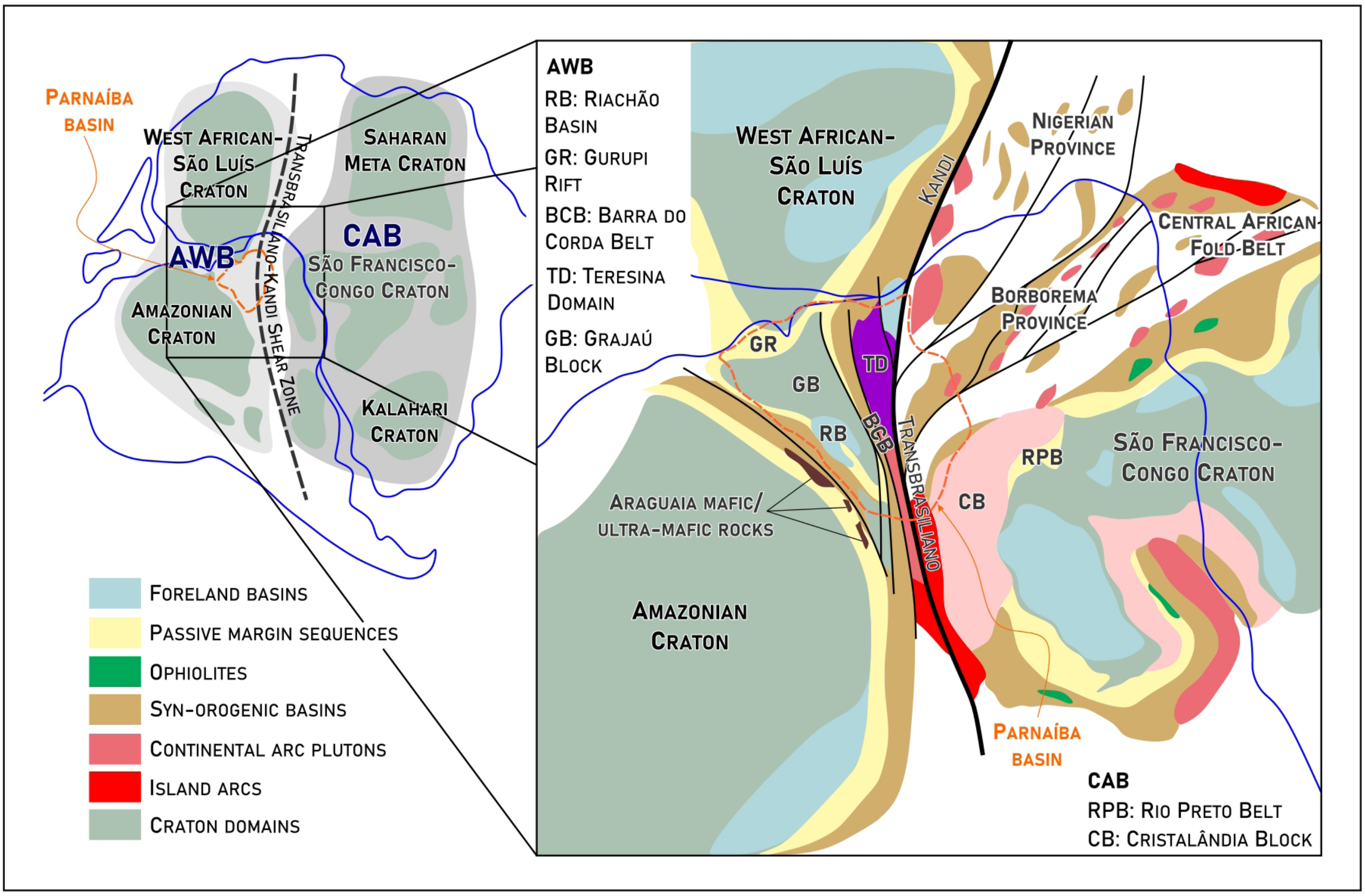

FIGURE 1. Geotectonic context from the reconstruction of Western Gondwana (between 630 - 500 Ma), showing the main intercontinental elements and structures in the vicinity of the Parnaíba Basin (adapted from Caxito et al. 2021 and Porto et al. 2022).

and tectonic structures that make up the internal framework of the basin. The most important of these is represented by the Transbrasiliano Zone and its extension along the African continent through the Kandi Lineament (Figure.1). This feature is interpreted as being the product of the amalgamation of several provinces and tectonic blocks that collided during the Brasiliano Orogeny, due to the closure of the Goiás-Farusian Ocean (Cordani et al. 2013; Brito Neves and Fuck 2014; Caxito et al. 2020, 2021; Tavares et al. 2022). Despite the recognized representativeness in regional studies, some aspects of its genesis and tectonic framework are not yet well established. This research sought a better understanding of structures associated with the Transbrasiliano Zone from geological and structural data obtained in outcrops and the interpretation of magnetic lineaments and seismic data. The study of paleotension fields, as well as the process of intrusion of magmatic bodies in this region were important for the discussion of the results and creation of the proposed models.

This research aimed to address in a multidisciplinary way the issue of low coverage of geological and geophysical data along the edge of the Parnaíba Basin and the uncertainties regarding the configuration of the tectonic framework of these regions, focusing on the southern edge (study area in Figure 2) with the support of data produced by the geophysical survey. Notoriously, when geophysical potential field data are analyzed in isolation, they present great ambiguity of solutions, where the heterogeneity of the sources and semi-infinite homogeneous bodies are the main limitations of these methods (Blakely 1996; Saltus and Blakely 2011). In an attempt to circumvent these issues, the research relied on 3D magnetization vector inversion and 2.5D joint modelling of magnetic and gravity data. Interpretation of reflection seismic and stratigraphic well data and magnetic susceptibility and relative density data obtained from outcrop samples were also integrated. The study allowed to better understand the tectonic setting and to obtain more robust geological models for the southern edge region of the Parnaíba Basin.

2. Geological Context

The Parnaíba Basin is located in Northeast region of Brazil and covers a surface area of approximately 600,000 km^2 (Figure 2), with sedimentary succession containing thicknesses of up to 3.4 km in sections located on rift or depocenter structures (Góes and Feijó 1994). The basin is bounded to the north and west by the São Luís and Amazon cratons, respectively, and to the south by the São Francisco craton. It is also bounded by the Borborema and Tocantins provinces, as well as a complex system of marginal mobile belts (e.g. Gurupi, Riacho do Pontal and Rio Preto).

The study area is located in the southern portion of the Parnaíba Basin, bordering the southwestern end of the Borborema Province and the northern portion of the São Francisco Craton (Figure 2). The geological framework of the study area is composed of gneissic-migmatitic cores, sedimentary metavolcanic and mafic-ultramafic granitoid

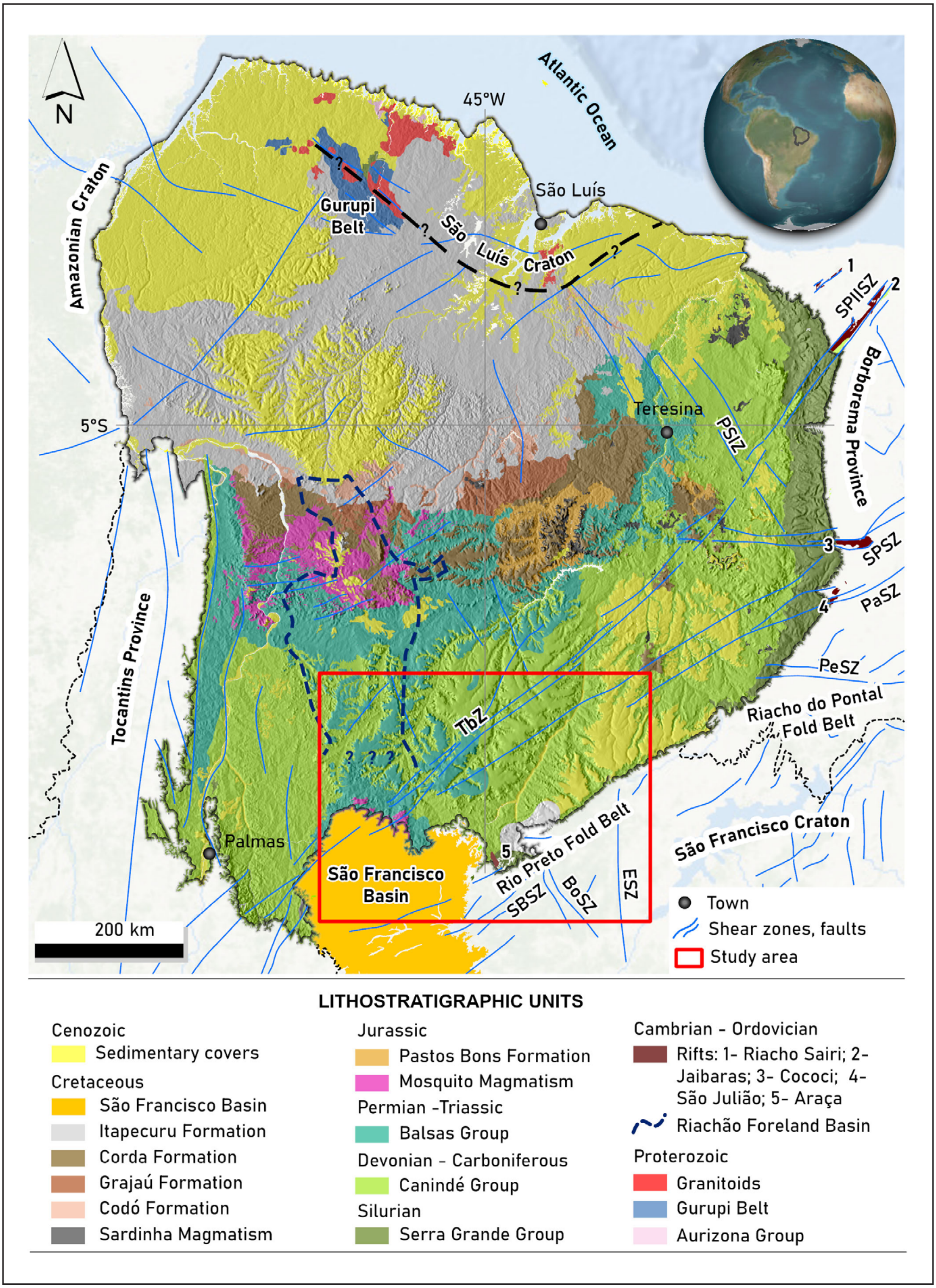

FIGURE 2. Simplified geological map of the Parnaíba Basin. Brazilian structures and shear zones: SPSZ - Senador Pompeu; PaSZ - Patos; PeSZ - Pernambuco; SBSZ - Sebastião Barros; BoSZ - Boqueirão; ESZ - Estreito; TbZ - Transbrasiliano Zone; PSIZ - Picos-Santa Inês Zone.

segments of various Archean and Paleoproterozoic age associated with the Sobradinho-Remanso and Júlio Borges complexes and the Cristalândia do Piauí Block (Prado and Vasconcelos 1991; Barros et al. 2020), northern portion of the São Francisco Craton (Figures 2 and 3). Proterozoic mobile belts composed essentially of shales and quartzites related to the Santo Onofre groups (Boqueirão and Estreito belts) and the Rio Preto Fold Belt (Barbosa and Sabaté 2004; Heilbron et al. 2016) also emerge. Overlying these units are sedimentary rock layers of the Phanerozoic Parnaíba and Sanfranciscana basins, as well as more recent coverings.

2.1. Archean/Paleoproterozoic basement

According to Prado and Vasconcelos (1991), the Sobradinho-Remanso Complex, which outcrops in the eastern portion of the study area (Figure 3), consists of migmatized gneisses, especially tonalitic orthogneisses, associated with granitoids, with subordinate granulites, intrusions of mafic-ultramafic rocks and subordinate supracrustals. In turn, the Cristalândia do Piauí Block (Barros et al. 2020), located in the southern and southeastern portion of the study area (Figure 3), is associated with the Rio Preto Fold Belt basement and is composed of Archean tonalitic to granidioritic orthogneisses, intruded by Paleoproterozoic metagranitoids of crustal signature, related to the Riacian-Orosirian Orogeny (Carvalho et al. 2019; Barros et al. 2020). The Júlio Borges Complex corresponds to a group of metaplutonic rocks of quartz-dioritic to tonalitic composition associated with mafic-ultramafic bodies (Carvalho et al. 2019).

2.2. Proterozoic covers and folded marginal belts

The Santo Onofre Group, delimited by the Boqueirão and Estreito shear zones (BoSZ and ESZ in Figures 2 and 3), is characterized by elongated relief structures in NNW-SSE and N-S directions, respectively, filled by terrigenous sedimentation following a triangular geometry open to the north (Figure 3) (Arcanjo and Braz Filho 2001; Loureiro et al. 2008). Caxito et al. (2014) interpret this corridor as the result of the evolution of a rift-type basin that was inverted during the Brasiliano Event and that is part of the Aulacogen Paramirim system (Heilbron et al. 2016).

In turn, the Rio Preto Group is composed of terrigenous metasediments and sequences of metavolcanosedimentary rocks associated with various granitoid bodies, deformed or not (Arcanjo and Braz Filho 2001; Carvalho et al. 2019) (Figure 3). The Rio Preto band has a general NE-SW orientation (Figure 1 and 2), which main structural feature is the presence of pronounced banding with low dip angle and vergence to NW, reflecting the transposition and parallelization of older folds, due to the involvement of these terrains in the Brazilian tangential tectonics (Caxito et al. 2014). The Sebastião Barros Shear Zone (SBSZ in Figure 3) corresponds to the main NE-SW transpressional compressional structure along the Rio Preto band (Carvalho et al. 2019).

2.3. Main tectonic blocks of the Parnaíba Basin

The first attempts to interpret the tectonic framework of the Parnaíba Basin were made from surface geology data, regional potential field data and few well data and 2D seismic sections. From this prior knowledge, in addition to the available information on the presence of geological structures mapped in its adjacencies and which have continuity under the basin, Brito Neves et al. (1984), Cunha (1986) and Góes et al. (1990) proposed the occurrence of cratonic cores of variable dimensions in the central region of the Parnaíba Basin, these features being limited to the east by the Transbrasiliano Zone (TbZ, Figure 2). Also noteworthy is the Picos-Santa Inês Lineament (PSIZ, Figure 2) which extends from the eastern end of the basin to the vicinity of the São Luís Craton, with a NW-SE direction.

The TbZ comprises a narrow band of NE-SW trending rocks approximately 4000 km long along the South American Platform, extending northward through the Kandi Lineament, NW of Africa (Figure 1). This intercontinental feature is represented by transcurrent faults, and is well characterized in potential field and seismic geophysical data. The TbZ completely crosses the eastern part of the Parnaíba Basin (Figure 2), which promotes a series of structures in the sedimentary rocks that are amenable to study (Daly et al. 2014; De Castro et al. 2014; Santos et al. 2018; Soares et al. 2018; Porto et al. 2022).

With the increase of more geophysical data, Cordani et al. (2009), interpreted four tectonic blocks in the basin region and associated them with micropaleocontinents that would have been separated in the Neoproterozoic, and which surrounding bands were established during the Brasiliano orogeny. De Castro et al. (2014) interpreted two phases of rifting in the formation of the basin, however this proposition was modified from the availability of new deep reflection and refraction seismic, seismological and magnetotelluric data (Daly et al. 2014; Tozer et al. 2017; Soares et al. 2018; Rocha et al. 2019; Schiffer et al. 2021).

Porto et al. (2022) proposed the occurrence of a new tectonic configuration for the Parnaíba Basin framework. They also revealed that the collisional tectonic scenario of the basement in the basin region contradicts the idea of a stable cratonic block, and presented new formation models that explain the heterogeneities observed in the crust and lithosphere. For the area of this study, these authors proposed the continuity of the Araguaia Leste, Grajaú and Cristalândia blocks of Piauí, the Rio Preto and Barra do Corda bands, in addition to the extension of the Goiás Magmatic Arc under the Parnaíba Basin. Recent data, based on 2D reflection seismic interpretation, gravity data and well data, have evidenced the existence of a pre-Silurian foreland basin, named Riachão Basin (Porto et al. 2018), in the NW portion of the study area (Figure 1 and 2).

2.4. Tectonostratigraphic context of the Parnaíba Basin

The tectonostratigraphic context of the Parnaíba Basin can be divided into five phases (Góes and Feijó 1994; Tozer et al. 2017; De Castro et al. 2018). The first is related to the oldest sedimentary rocks preserved in and around the basin (Riachão and Ubajara basins), interpreted as being foreland-type (Porto et al. 2018). A second phase is represented by a tectonic relaxation due to the late Brasiliano orogenic process that allowed the formation of rift-type basins (e.g. Jaibaras and Cococi) along zones of past crustal weakness (Pedrosa Jr. et al. 2015; 2017; De Castro et al. 2016).

Tozer et al. (2017) demonstrated, through gravity data, that the subsidence mechanism for the formation of the Parnaíba

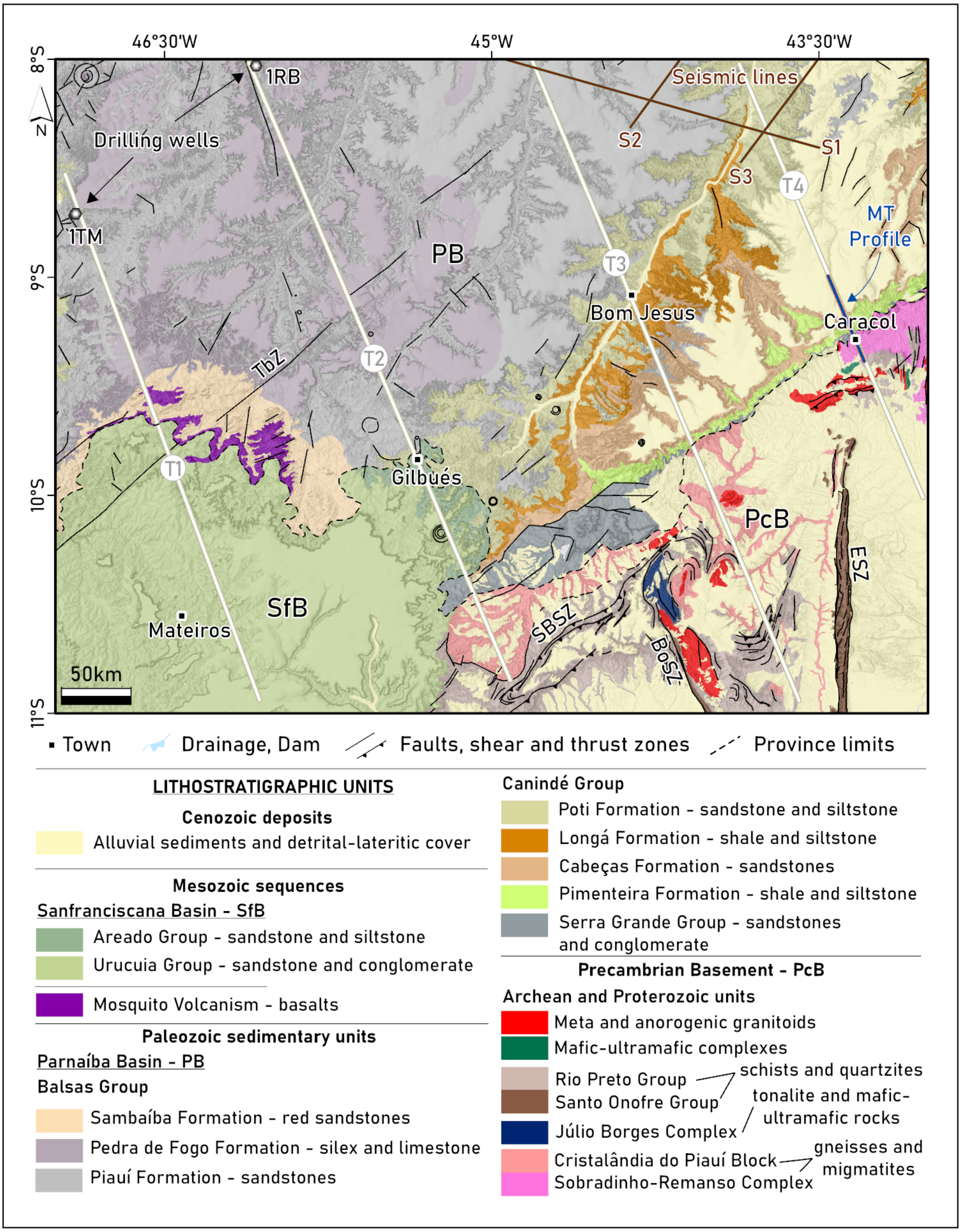

FIGURE 3. Simplified geological map of the study area. Brasilian structures: SBSZ - Sebastião Barros Shear Zone; BoSZ - Boqueirão Shear Zone; ESZ - Estreito Shear Zone. TbZ - Transbrasiliano Zone. T1 to T4 represent the transects used for modeling the magnetic and gravity data.

Basin is compatible with a dense intrusive body, positioned in the lower crust, which generated an overburden and flexed the crustal surface. This process was responsible for a third phase, characterized by the sedimentary filling of the basin in the early Silurian. The Serra Grande Group, composed of the Ipu, Tianguá and Jaicós formations, corresponds to the oldest megasequence of the basin (Figures 2 and 3). This succession consists of sandstones with intercalations of siltstones and shales, interpreted as fluvial, glacial marine and shallow marine environments (Caputo and Lima 1984). The end of deposition of the Serra Grande Group is marked by a regional discordance associated with the Caledonian Orogeny (Góes and Feijó 1994). Sedimentation in the basin continued with the deposition of the Canindé Group, divided into the Itaim, Pimenteira, Cabeças, Longá and Poti formations, between the Middle Devonian and early Carboniferous (Figures 2 and 3). This sequence is characterized by fluvio-deltaic and shallow marine depositional systems (Góes and Feijó 1994). Another regional discordance during the Upper Carboniferous, associated with the Hercynian Orogeny, resulted in a reactivation along the NW coast of Africa, and this marks the end of deposition in the Canindé Group (Góes and Feijó 1994). With decreasing subsidence rates, the Balsas Group was deposited between the Upper Carboniferous and Middle Triassic. It is divided by the formations Piauí, coastal and desert sandstones; Pedra de Fogo, with rocks associated with sabka environments; Motuca, with depositions related to desert and lacustrine environments and; Sambaíba, essentially characterized by desert environment (Figures 2 and 3) (Góes and Feijó 1994; Vaz et al. 2007).

The last discordance associated with the sedimentary filling of the basin is associated with the Alleghenian or Gondwanides Orogeny (Zalán 1991). This event affected sedimentation in the basin and caused the migration of the depocenter to W-NW (Tozer et al. 2017), accompanied by the deposition of sediments of the Pastos Bons Formation (Figure 2), restricted to the central portion of the basin, together with the formation of extensive basaltic flows on the western side (Mosquito Formation: average age $^{40}Ar/^{39}Ar$ 199 ± 2.4 Ma, Merle et al. 2011). The origin of this magmatism has been attributed to the Central Atlantic Magmatic Province (CAMP), a precursor event to the fragmentation of the supercontinent Pangea and opening of the Central Atlantic Ocean (Baksi and Archibald 1997; Merle et al. 2011). Finally, the last phase, initiated from the process of breakup of Western Gondwana and opening of the Atlantic Ocean, occurs a new magmatic pulse (Sardinha Formation: average age $^{40}Ar/^{39}Ar$ 129 and 124 Ma, Bellieni et al. 1992) and the formation of deposits in the Grajaú sub-basin (Codó, Corda, Grajaú and Itapecuru formations, Figure 2), under arid climate and characterized by fluvial, lacustrine and shallow platform systems (Vaz et al. 2007).

The youngest sedimentary sequence of the study area, deposited from the Cretaceous, corresponds to the rocks of the Sanfranciscana Basin, represented in its northern portion by the Areado and Urucuia groups (Figure 3). The formation of these units was dominated by fluvial-lacustrine and fluvial-eolian systems (Campos and Dardene 1997). Recent sediments, associated with alluvium and detrital-lateritic covers, outcrop throughout the study area.

2.5. Main tectonic features in the W of the Borborema Province

The Borborema Province, along its western portion, represents the Precambrian basement of the northeastern part of the Parnaíba Basin (Brito Neves et al. 1984; Cunha 1986; Porto et al. 2022) (Figures 1 and 2). It is characterized by alternating metaigneous domains and metasedimentary belts of variable ages, separated by a large system of transcurrent shear zones that, in turn, divide the province into Northern, Central and Southern domains. Namely, the Senador Pompeu (SPSZ), Patos (PaSZ), Pernambuco (PeSZ) and Sobral-Pedro II (SPIISZ) shear zones and their extension through the Transbrasiliano Zone (TbZ) (Figure 2) are important geological and structural features in the study of the Parnaíba Basin.

3. Data and Methods

The geophysical data used were obtained by means of airborne magnetometry, gamma spectrometry and gravity surveys (Figure 4). These data were collected by independent projects contracted by the Geological Survey of Brazil (SGB) and the Brazilian National Agency for Petroleum, Natural Gas and Biofuels (ANP). Ground gravity data (Figure 4), compiled by Oliveira (2008), were also used to generate Bouguer anomaly maps. Seismic sections and well data (Figure 4) were used to calibrate the geophysical models. Field geological reconnaissance of the main units at the southern edge of the basin was carried out, as well as rock sampling for the extraction of magnetic susceptibility and density measurements. These data also served to perform a stress field analysis of the reactivations and accommodation of Mesozoic magmatism in the study area.

3.1. Airbone gamma-ray spectrometric and magnetic data

The airborne datasets have flight line spacing ranging from 6000 m and 500 m, flight height of 800 m and 100 m, and flight line directions N-S and E-W (Table 1). These data were leveled and interpolated by the bidirectional method in a square cell of ¼ of the spacing of the flight lines of each project and again leveled and integrated by the gridkniting method in a square cell of 500 m side.

The gamma-ray spectrometric maps were used to recognize units in the field and to define more precisely the geological contacts, mainly between the basin and the basement. The magnetic anomaly in the study area shows the magnetic sources without the effects of the Earth's magnetic field. In order to increase the signal-to-noise ratio, highlight specific features and estimate the depth of the magnetic sources, the following maps were obtained from the application of different techniques: 1) magnetic pole reduction (Figure 5a); 2) matched filter; 3) 3D Euler deconvolution; 4) total gradient and; 5) pseudo-gravity transformation.

3.2. Gravity data

The airborne and ground-based gravity dataset (Figure 4) was organized and leveled in a database with files arranged in XYZ format. The Bouguer anomaly (Figure 5b) was obtained by interpolating the data on a regular 1.5 km grid using the method of least curvature (Swain 1976; Briggs 1974).The power spectrum of the gravity signal (Spector and Grant 1970) was generated in order to obtain a better result with respect to the spectral separation of shallow and deep sources. The regional and residual components of the gravity field were separated by means of a Gaussian filter which is based on low-pass and high-pass applications of the gravity signal.

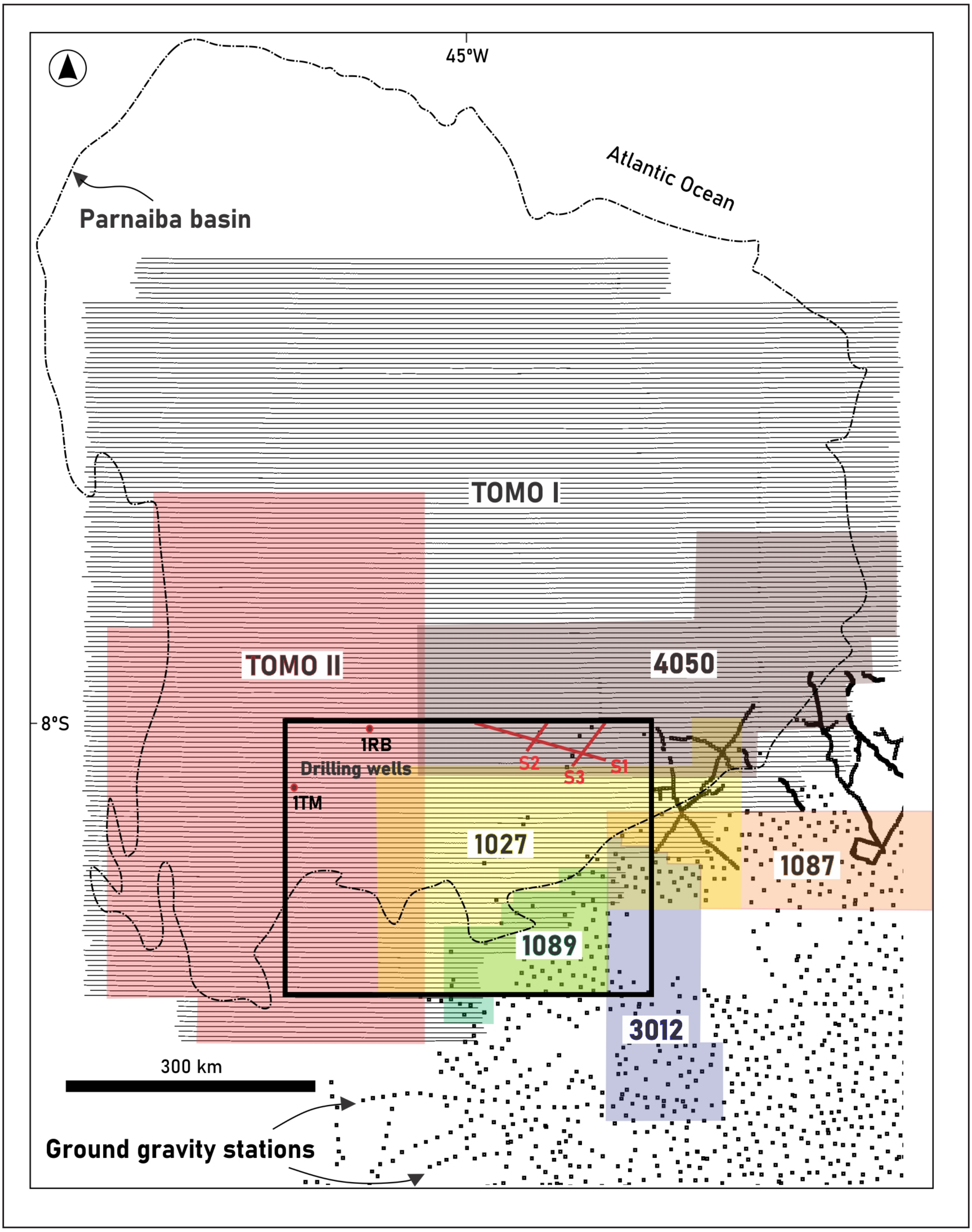

FIGURE 4. Map with the location of the geophysical data and projects used in the study of the southern edge of the Parnaíba Basin. The red lines represent the seismic sections used in the study. Table 1 shows the characteristics of each of the airbone surveys.

3.3. Acquisition of magnetic susceptibility and density data

Magnetic susceptibility and density property measurements were carried out on rocks directly at the outcrops, and on laboratory treated outcrop samples. For this purpose, the Kappameter KT-10 S/C portable equipment was used to obtain the magnetic susceptibility measurements, while the density measurements were obtained and calculated from the Archimedes principle, based on the mass (kg) and volume (m^3) of the samples. A total of 20 rock samples from the basin and basement units were collected for the determination of relative density values and 35 magnetic susceptibility measurements were taken from outcrops of basin and basement rocks (Table 2).

TABLE 1. General characteristics of the airbone geophysical surveys used in the study of the southern edge of the Parnaíba Basin.

Airbone surveys	Code	Year	Flight-line spacing (m)	Flight-line direction	Flight height (m)	Magnetic field declination	Magnetic field inclination	Magnetic field strenght (nT)
Borda Sul da Bacia do Parnaíba	1027	1976/1977	2000	N-S	150	-18.88°	-6.34°	25625.5
Bacia do Maranhão (Parte Sul)	4050	1989	3000	N-S	800	-20.72°	-8.37°	25657.4
Campo Alegre de Lourdes - Mortugaba	3012	2005	500	E-W	100	-21.87°	-18.9°	24739.3
Cristalândia do Piauí	1089	2009	500	N-S	100	-21.91°	-19.93°	24584.2
Médio São Francisco	1087	2008/2009	500	N-S	100	-21.9°	-18.5°	24893.9
Identificação de áreas com ocorrência potencial de petróleo e gás na Bacia do Parnaíba - ANP-USP	TOMO I	2005/2006	6000	E-W	500/800	-20.93°	-14.23°	24734.8
	TOMO II	2004/2006	500	N-S	100	-20.92°	-13.86°	24757.9

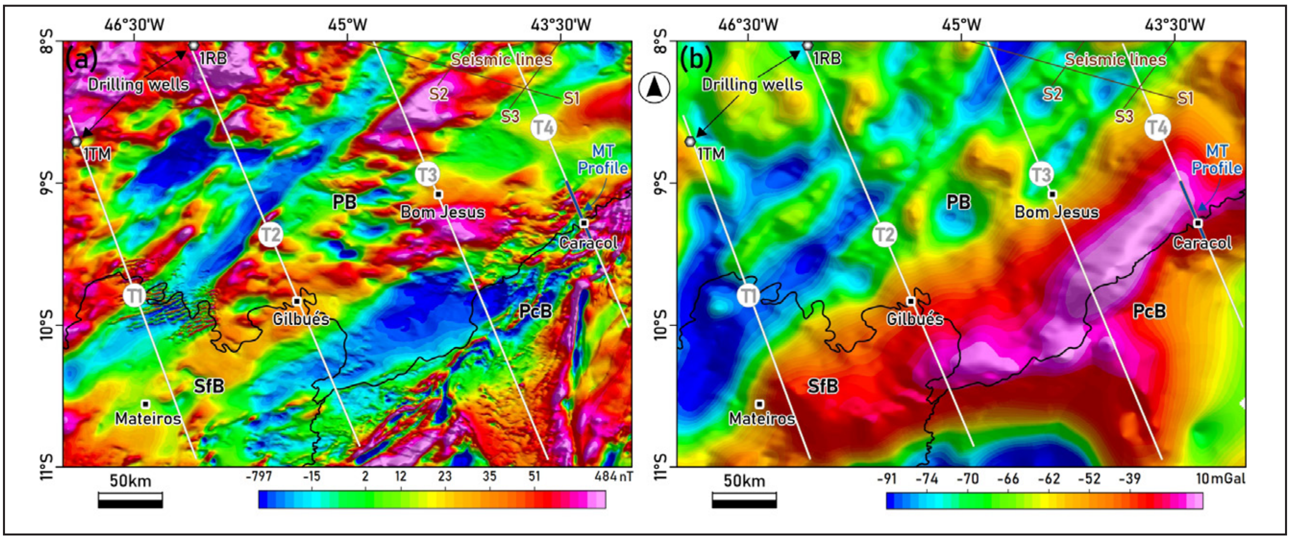

FIGURE 5. Maps of pole-reduced magnetic anomaly (a) and Bouguer gravity anomaly (b). T1 to T4 are the transects used for the 2.5D joint magnetic-gravity modeling. PB: Parnaíba Basin; SfB: Sanfranciscana Basin; PcB: Precambian Basement.

TABLE 2. Fluctuations in the results of density tests and magnetic susceptibility measurements on some rock samples and outcrops throughout the study area. Negative magnetic susceptibility values in the Precambrian basement region were generated during the magnetic data inversion process.

Crustal Domain	Geological Unit	Lithology	Magnetic susceptibility (SI units)	Density (kg/m³)
Sanfranciscana basin	Urucuia Group	Sandstones	0.000	2300
Parnaíba basin	Mosquito magmatism	Basalts and gabbros	0.051 - 0.150	2720 - 2760
	Balsas Group	Siltstones and sandstones	0.000	2385 - 2415
	Canindé Group	Shales, sandstones and siltstones	0.000 - 0.001	2420 - 2450
	Serra Grande Group	Sandstones and conglomerates	0.000	2425 - 2500
Precambrian basement	Metagranitoids	Granites	-0.005 - 0.008	2600 - 2608
	Rio Preto Group	Schists and marbles	-0.036 - 0.032	2605 - 2615
	Sobradinho-Remanso Complex	Gneiss and leucogranites	-0.040 - 0.002	2615 - 2652
	Cristalândia do Piauí Block	Orthogneiss	-0.065 - 0.045	2645 - 2735

3.4. Reflection seismic and stratigraphic well data

Time-migrated 2D reflection seismic data were used, including two NE-SW sections, with approximate lengths of 40 and 60 km, and a larger NW-SE section with a length of approximately 160 km (Figures 4 and 6). The ANP's Exploration and Production Database (BDEP) has made the migrated seismic sections available in SEGY format. In order to facilitate the interpretation of these data, we used the seismic pseudo-relief attribute to highlight and generate a shaded aspect of the amplitudes of the seismic reflectors. We did not convert the sections to depth, but only estimated them based on other works that used the same dataset (e.g., Cunha 2011; De Castro et al. 2016). These data were used to interpret the sedimentary succession in the NE portion of the study area and also, together with well data and magnetotelluric data, to assist in the elaboration of geological models. The interpreted seismic sections are shown in Figure 6.

Data from stratigraphic wells are scarce in the study area, except in the extreme NW, where two stratigraphic wells (1TM and 1RB) were used for the survey at the southern edge of the basin (Figures 4 and 7). The T1 and T2 transects over the location of the two wells allowed a calibration of the features interpreted in the model with the information from the wells. Well 1TM reached a maximum depth of 1690.3 m and reached the basement at a depth of 1685 m (Figure 7). Well 1RB has a maximum depth of 1836.5 m, but it did not reach the basement (Figure7). Gamma ray (GR), spontaneous potential (SP) and electrical resistivity (IDL) profile information from the two wells were used for stratigraphic interpretation.

3.5. Inversion and modeling of magnetic and gravity data

The magnetic anomaly data were used to investigate and obtain the magnetic susceptibility distribution at depth and the geometry of magnetic bodies in the upper portion of the crust. For this, we used the automatic 3D magnetization vector inversion technique (Ellis et al. 2012; MacLeod and Ellis 2013, 2016). This allows us to orient the magnetization direction to best fit the observed data, based on Tikohonov's minimum gradient regularization. A smoothness link is used to constrain abrupt variations between cells (Ellis et al. 2012). This technique also minimizes instabilities caused by low magnetic latitude anomalies and remnant nature (MacLeod and Ellis 2013). The inversion model corresponds to the subsurface discretized into voxel cells.

The direct modeling of magnetometry and gravimetry data from the algorithms developed by Talwani et al. (1959), Talwani and Heirtzler (1964) and Won and Bevis (1987), consists of the creation and interactive manipulation of closed polygons in a simple way that separate media with different physical properties. To do this, the code compares and adjusts the values of the calculated anomalies to the observed values. Seequent's GM-SYS platform was used to apply this method. The joint modeling was performed along 4 regional transects of NW-SE direction (Figure 5).

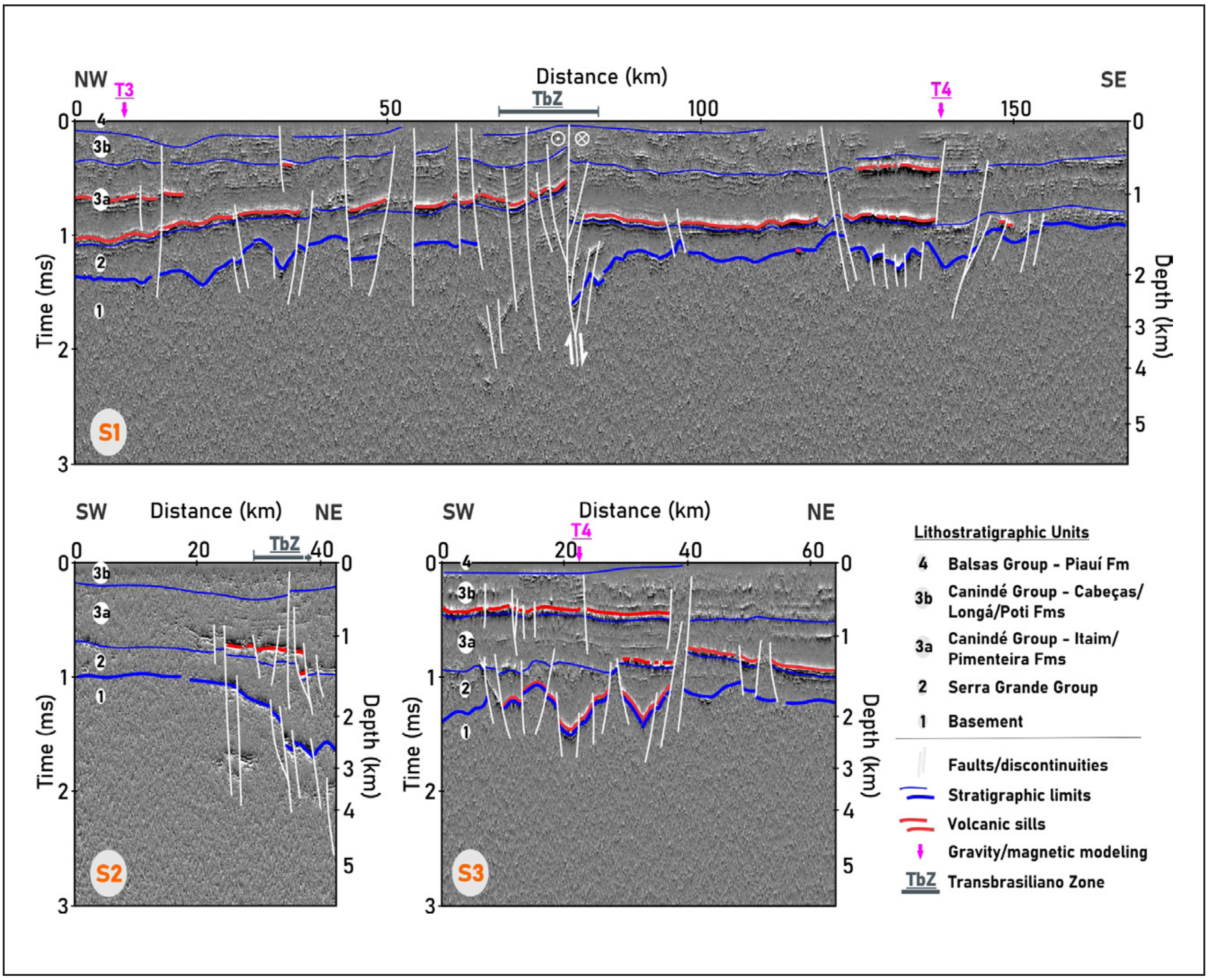

FIGURE 6. Seismic sections S1, S2 and S3 interpreted according to the lithostratigraphic units present in the southern edge of the Parnaíba Basin and the main structural features that occur along the study area, such as a discontinuous reflector pattern along the Transbrasiliano Zone (TbZ). The thicker blue line represents the contact of the basin with the basement. These data are located in the NE portion of the study area (Figure 4).

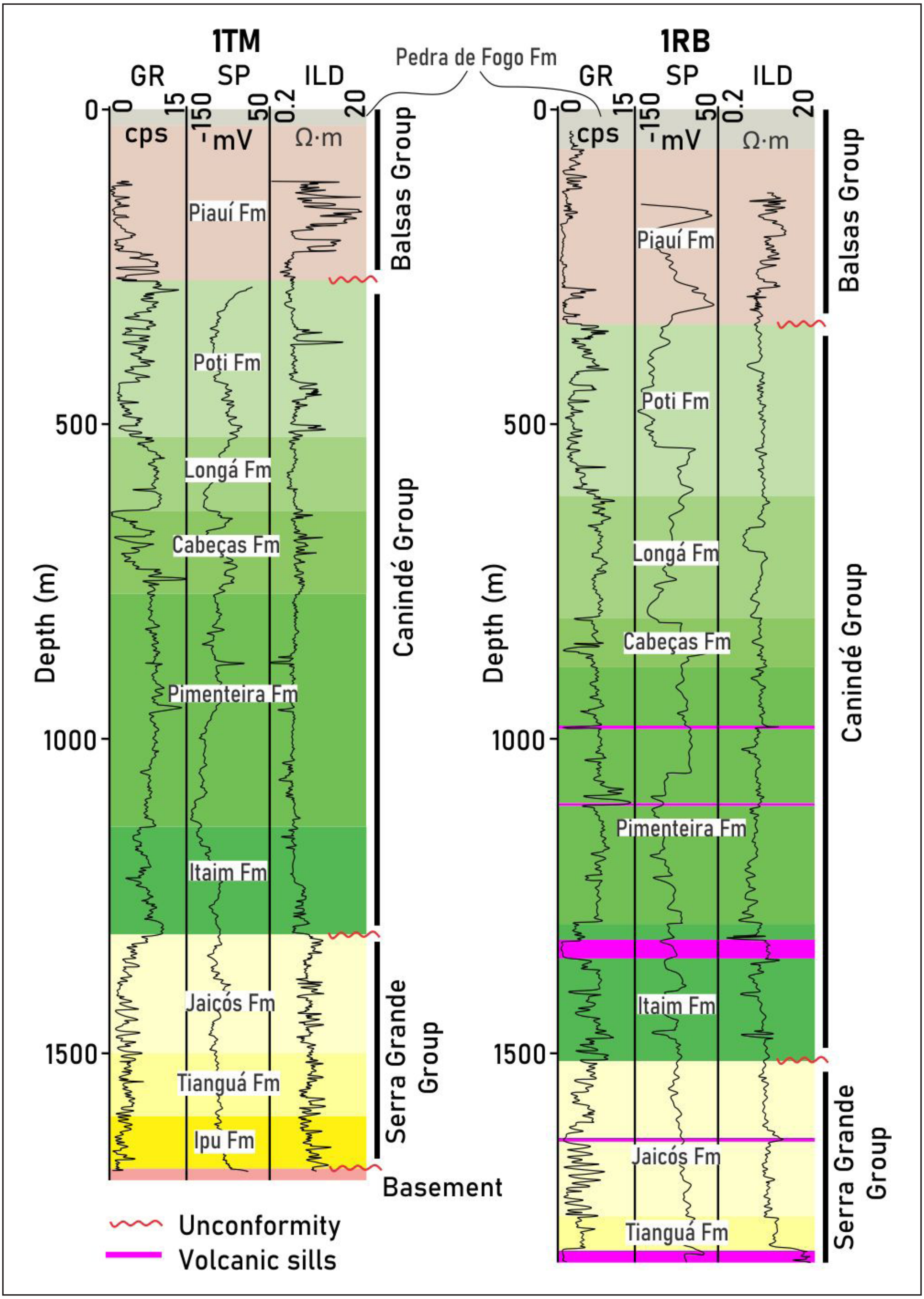

FIGURE 7. Stratigraphic wells 1TM (left) and 1RB (right) and the logs that were used in the research. These data were used to support the data modeling. The location of the wells is shown in Figure 4.

4. Results and Discussions

4.1. Regional interaction between provinces and tectonic blocks

Along the southern edge of the Parnaíba Basin and the study area, there is the extension of several geological and tectonic structures that make up the internal framework of the basin, the most important of which is represented by the Transbrasiliano Zone (TbZ in Figure 8). In the study area, two suture zones are also interpreted, one of approximate E-W direction, which occurs between the north of the São Francisco Craton and its marginal bands and the southern part of the Borborema Province and the other, of NE-SW direction with inflection to N-S, marked in the region of the extension of the Grajaú Block and the Goiás Magmatic Arc and along the Barra do Corda Belt (Figure 8).

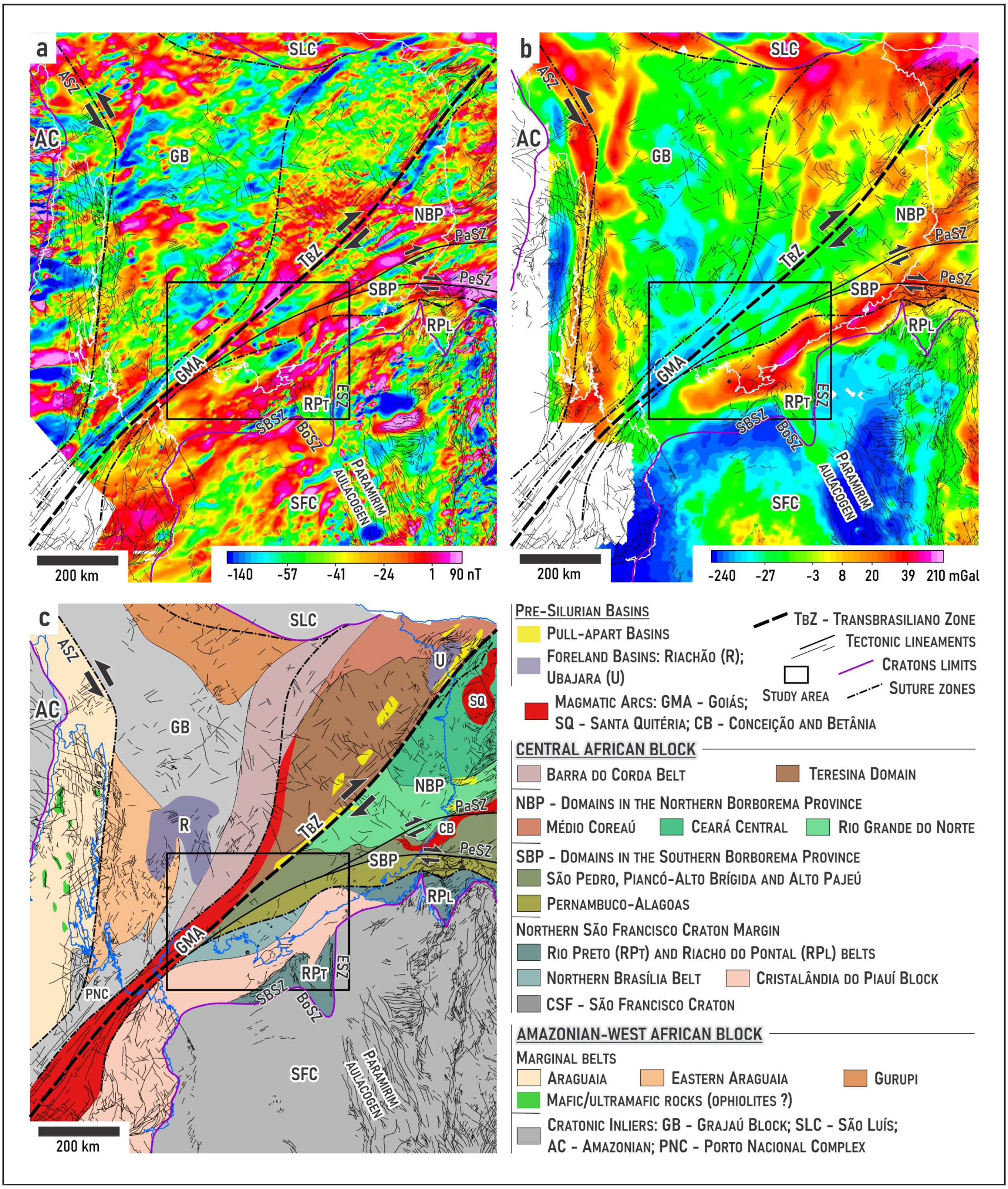

FIGURE 8. Maps of magnetic (a) and gravity Bouguer anomalies (b) along the Borborema and Araguaia provinces, the Parnaíba Basin and the northern portion of the São Francisco Craton and its marginal belts. Tectonic framework of the Parnaíba Basin and its surroundings (c) (adapted from Porto et al. 2022). Brazilian structures and shear zones: PaSZ - Patos; PeSZ - Pernambuco; SBSZ - Sebastião Barros; BoSZ - Boqueirão; ESZ - Estreito; TbZ - Transbrasiliano Zone.

The oldest segments that make up the structural framework in the study area are formed by the northern portion of the São Francisco Craton (SFC in Figure 8), structured within the Central African Block (CAB in Figures 1 and 8) and by the Grajaú Block (GB in Figure 8), interpreted as the pre-Brazilian metamorphic basement, which in turn was developed along the Amazonian-West African crustal megablock (AWB in Figures 1 and 8). The regional geophysical signature shows that the northern portion of the SFC is represented by intermediate to low magnetic anomalies with alignments of preferential NE-SW directions. A strong NNW-SSE magnetic, gravity and structural trend is represented by the Aulacogeno Paramirim, which extends from the central portion of the SFC to the Rio Preto Belt region, through the Boqueirão and Estreito shear zones (RPT, BoSZ and ESZ in Figure 8). The gravity anomaly along the NW edge of the SFC is marked by low values, with increasing positive values in the vicinity of the Rio Preto Belt (SE of the study area in Figure 8b). This gravity pair has been interpreted and accepted as a suture zone between the craton and the southern domain of the Borborema Province (Oliveira 2008) (SFC and SBP in Figure 8).

The Grajaú Block is interpreted to be a reworked cratonic inlier at the eastern margin of the Amazon Craton (AC in Fig. 8) during the Neoproterozoic (Hodel et al. 2019; Assis et al. 2021). Magnetic and gravity data mark the boundaries of this unit and reveal negative anomalies in the central region, possibly suggesting greater crustal thickness and the association of this domain with a cratonic inlier (Figures 8a and 8b). The tectonic fit along the AWB is completed by the Araguaia East Belt (Figure 8c) and the Riachão Basin (R in Figure 8c), structured within the Grajaú Block (Porto et al. 2018). These units cover the NW portion of the study area, which crustal thickness is of the order of 39 to 40 km (Queiroz 2019).

On the side of the CAB, Porto et al. (2022) suggested the extension of the Goiás Magmatic Arc (GMA in Figure 8) along a narrow strip of NE-SW direction with inflection to N-S beneath the Parnaíba Basin. Magnetic and gravity reliefs reveal a pattern of anomalies aligned along NE-SW trends, with a stress vector associated with a generalized compression along the WNW-ESE direction and which is responsible for the dextral kinematics of the TbZ (Figure 8). Together with the GMA, these authors proposed the creation of two domains structured along the TbZ. The first is the Teresina Domain (Daly et al. 2014; De Castro et al. 2014), located in the northern portion of the study area, and which is interpreted as a remnant block from the collision between the CAB and AWB megablocks (Figures 1 and 8). The second corresponds to the Barra do Corda Belt, interpreted as a mobile belt or transpressional shear zone associated with a paleosuture zone (Soares et al. 2018; Solon et al. 2018; Schiffer et al. 2021). These features have a similar magnetic and gravity pattern, with short-wavelength anomalies and NE-SW direction occurring in the northern and central-western portions of the study area and on the western flank along the TbZ. (Figure 8c)

The northern marginal portion of the SFC is characterized by the presence of distinct tectonic units that were brought together during the Brasiliano. The Cristalândia Block of Piauí corresponds to the Rio Preto Belt basement and is considered a metacratonic domain developed in processes of crustal accretion and reworking (Barros et al. 2020).This block, which would have merged with a narrow portion of the Brasília Belt to the north (Figure 8c), is characterized by a very expressive gravity anomaly of NE-SW direction and wavelength of the order of 100 km (Figure 8b). It also presents a strong magnetic anomaly and a magnetic low in the region of the Brasilia Belt, which reinforces the division of these units (Figure 8a).

The boundaries of the Rio Preto Belt (RPT in Figure 8) are well marked by expressive and short-wavelength (< 10 km) magnetic and gravity anomalies and which are configured by shear and thrust zones, such as the SBSZ, BoSZ and ESZ (Figure 8). The inner part of the RPT is dominated by dipolar magnetic anomalies, which give the signal large amplitude and are associated with rocks of high magnetic susceptibility (Figure 8a) (Carvalho et al. 2019). The gravity anomaly is characterized by intermediate relief and marks a possible transition between the rocks of the SFC, through the Paramirim Aulacogen, to the gravity high associated with the Cristalândia Block of Piauí, buoyed by the BoSZ and ESZ (Figure 8b). Recently, Romero-Beltran et al. (2022), revealed an electrical resistivity model in a transect in this region and suggested the presence of discontinuities in the crust associated with fluid interactions and structural deformations that occurred in the Cristalândia Block of Piauí.

The tectonic framework of the study area is completed with the rocks of the western portion of the Borborema Province. Two segments are individualized within the province: the Northern Domain (NBP), which is represented by the Middle Coreaú, Central Ceará and Rio Grande do Norte subdomains (Figure 8c), and the Southern Domain (SBP), marked by important shear zones, such as Patos (PaSZ) and Pernambuco (PeSZ) and which delimit the São Pedro, Piancó-Alto Brígida and Alto Pajeú subdomains with the Pernambuco-Alagoas domain and enter the Parnaíba Basin region through the NE portion of the study area (Figure 8c). An important feature of this region is the presence of short wavelength magnetic anomalies (< 5 km) and NE-SW and E-W direction with a very rugged magnetic relief (Figure 8a). Another relevant point is the presence of rift-type or pull-apart basins that outcrop in this region and that are also interpreted from seismic and gravity data (Daly et al. 2014; De Castro et al. 2014) (Figure 8c). This feature reveals that the western region of the Borborema Province is the crustal portion of greatest weakness along the structural framework of the Parnaíba Basin.

4.2. Geophysical-structural framework along the southern edge of the basin

The pole-reduced magnetic anomaly map shows sharply contrasting relief, with values ranging from -797 nT to values close to 500 nT (Figure 5a). Regional anomalies in the Parnaíba Basin region show a strong trend with NE-SW direction, which was influenced by the formation and subsequent reactivation of structures of the Transbrasiliano Zone (PB in Figure 5a). The SW region of the study area, where the sedimentary rocks of the Sanfranciscana Basin (SfB in Figure 5a) outcrop, shows a similar magnetic signature, however the pattern of anomalies is smoother and suggests a greater thickness of the sedimentary cover. In the region where the Precambrian basement rocks outcrop (PcB in Figure 5a) the magnetic relief presents strong contrasts, with shorter wavelength anomalies and NE-SW, NW-SE and N-S preferential directions.

To analyse the behaviour of the magnetic anomaly at different depth levels the Matched Filter technique (Phillips 2001) was used, starting from the individualization of three primary magnetic zones (Figure 9a, b, c). The first zone represents deep magnetic sources, ranging from approximately 20 to 30 km depth. These anomalies are associated with middle and lower crustal features and are suggestive of upper crustal discontinuities reaching greater depths, such as the TbZ and some basement structures (Figure 9a). An intermediate zone shows anomalies associated essentially with upper crustal features, which magnetic sources have depths of approximately 5 to 8 km (Figure 9b). In this depth interval, the strong influence of the TbZ deforms the rocks of the basement and the Parnaíba and Sanfranciscana basins. Magnetic alignments of E-W direction may be associated with open fractures and are well marked in the north-central portion of the study area. Finally, the shallowest zone is composed of short-wavelength anomalies representing magnetic sources between 0.5 and 1 km depth (Figure 9c). This interval interprets the occurrence of geological features that outcrop or are close to the surface, such as magmatic rocks related to the Mosquito Formation, punctual features characterized by circular structures associated with kimberlitic bodies and the geological units and structures of the basement, mainly mafic-ultramafic rocks of the Rio Preto and Santo Onofre groups, the Júlio Borges Complex and other indiscriminate complexes, as well as shear zones (Figures 3 and 9c).

The techniques of total gradient and Euler deconvolution (Thompson 1982; Nabighian 1984), were used in order to increase the interpretation of regional and local features, improve the limits of magnetic sources and estimate the depth of sources in the shallowest portion of the crust. It was possible to define the main magnetic alignments and domains present in the study area. The total gradient map (Figure 9d) represents the magnetic anomaly centered over the source and is ideal for qualitative analyses. The results obtained with this technique show similarities with the information of the intermediate and shallow zones obtained with the application of the matched filter technique. Euler solutions (Figure 9e) were obtained for three depth intervals: solutions reaching depths greater than 5 km, which represent basement features, and probably the continuity of these structures along the upper crust, positioned in higher concentrations along the TbZ and in the NE portion of the area; solutions between 1.5 and 3 km depth (Figure 9e), which represent structures of the sedimentary cover of the Parnaíba and Sanfranciscana basins and associated with the shear zones of the basement (SBSZ, BoSZ and ESZ, Figure 9e), and; solutions with depths below 0.5 km, strongly associated with the dikes and sills of magmatic rocks intruded in the sedimentary succession of the Parnaíba Basin and features of the shallow basement.

The main magnetic lineaments and four main magnetic domains were established and interpreted for the study area (Figure 9f). High amplitude magnetic anomalies are concentrated in the south/southeast region of the area and are associated with the rocks of the Rio Preto and Santo Onofre belts and the mafic-ultramafic complexes of Júlio Borges and other indiscriminate ones (Figure 3; H1 in Figure 9f). This domain also composes the structural framework of the Parnaíba Basin in the eastern portion of the area. To the west, the H2 magnetic domain (Figure 9f) is characterized by high-amplitude, short-wavelength anomalies (<1 km), ENE-WSW preferential direction, and is also characterized by shallow magnetic sources (<0.5 km depth). This domain is exclusively represented by magmatic rocks of the Mosquito Formation and by kimberlitic intrusions (Figure 3; H2 in Figure 9f).

A second magnetic domain is characterized by anomalies of intermediate to high amplitudes (IH1 to IH4 in Figure 9f). The IH1 subdomain has segmented and curvilinear anomalies and is attributed to rocks of the Rio Preto Group and also metagranitoid bodies, and is well delimited by the Boqueirão and Estreito shear zones (Figure 9f). The IH2 subdomain has a main trend ENE-WSW, and the northern boundary is well marked by a rectilinear magnetic anomaly of approximately 200km in length (Figure 9f). This feature may be related to an important fault developed along the Cristalândia Complex of Piauí at the edges of the Parnaíba and Sanfranciscana basins (Figure 3; IH2 in Figure 9f). The IH3 subdomain presents a sigmoidal anomaly pattern, while IH4 presents a NE-SW structuring with strong influence of the TbZ (Figure 9f). This region is associated with the continuity of geological features of the southern portions of the Teresina Domain and the Barra do Corda Belt (Porto et al. 2022) (Figures 8c and 9f).

The third domain is represented by magnetic relief of intermediate to low anomalies (IL1 and IL2 in Figure 9f). These domains are placed in the central and north/northwestern parts of the study area and are strongly associated with tectonics governed by the TbZ. This region, located completely on the sedimentary rocks of the Parnaíba and Sanfranciscana basins, is correlated to the continuity of tectonic features of the basement of the southern part of the Borborema Province (Figure 8c; IL2 in Figure 9f) and the extension of the rocks of the Goiás Magmatic Arc, Grajaú Block and the eastern Araguaia domain (Porto et al. 2022) (Figures 8c and 9f).

Finally, the magnetic domain with weaker amplitudes and absence of total gradient is located between L1 and L3 (Figures 9d and 9f). L1 is located in the extreme southeast of the area, has a gentle magnetic relief with some linear anomalies of NE-SW direction that are associated with dikes that occur along the São Francisco Craton and its marginal belts (Carvalho et al. 2019; Uchôa Filho et al. 2019; Vale et al. 2022). The extension of the weakly magnetic rocks of the Pernambuco-Alagoas domain is well represented by subdomain L2, which is covered by the sedimentary rocks of the Parnaíba Basin (Figures 3 and 9f). The L3 domain covers the southern part of the study area. Possibly, the softer magnetic contrast in this region is associated with the gneissic-migmatitic rocks of the Cristalândia Complex of Piauí and also of the northern portion of the Brasília Belt (Porto et al. 2022) (Figures 8c and 9f).

The Bouguer gravity anomaly map (Figure 10a) shows values ranging from -91 to 10 mGal. In the basement region (PcB), anomalies with higher values have main trends N-S, NE-SW and NW-SE and are associated with the large structures present in the rocks that make up the Rio Preto and Santo Onofre groups and in the Júlio Borges Complex. Lower gravity values in this region should represent older and thicker crustal features associated with the Cristalândia do Piauí and Sobradinho-Remanso complexes (north of the SFC). The Parnaíba Basin region is dominated by gravity anomalies with a NE-SW preferential direction, and this is well characterized by anomalies segmented with high and low values of the gravity field with strong influence of the TbZ (Figure 10a). The SfB region presents a gravity pattern similar to that of the Parnaíba Basin, and is well represented by the continuity of basement structures, as well as the attenuation of the high gravity signal that is more expressive at the edge of the Parnaíba Basin (Figure 10a).

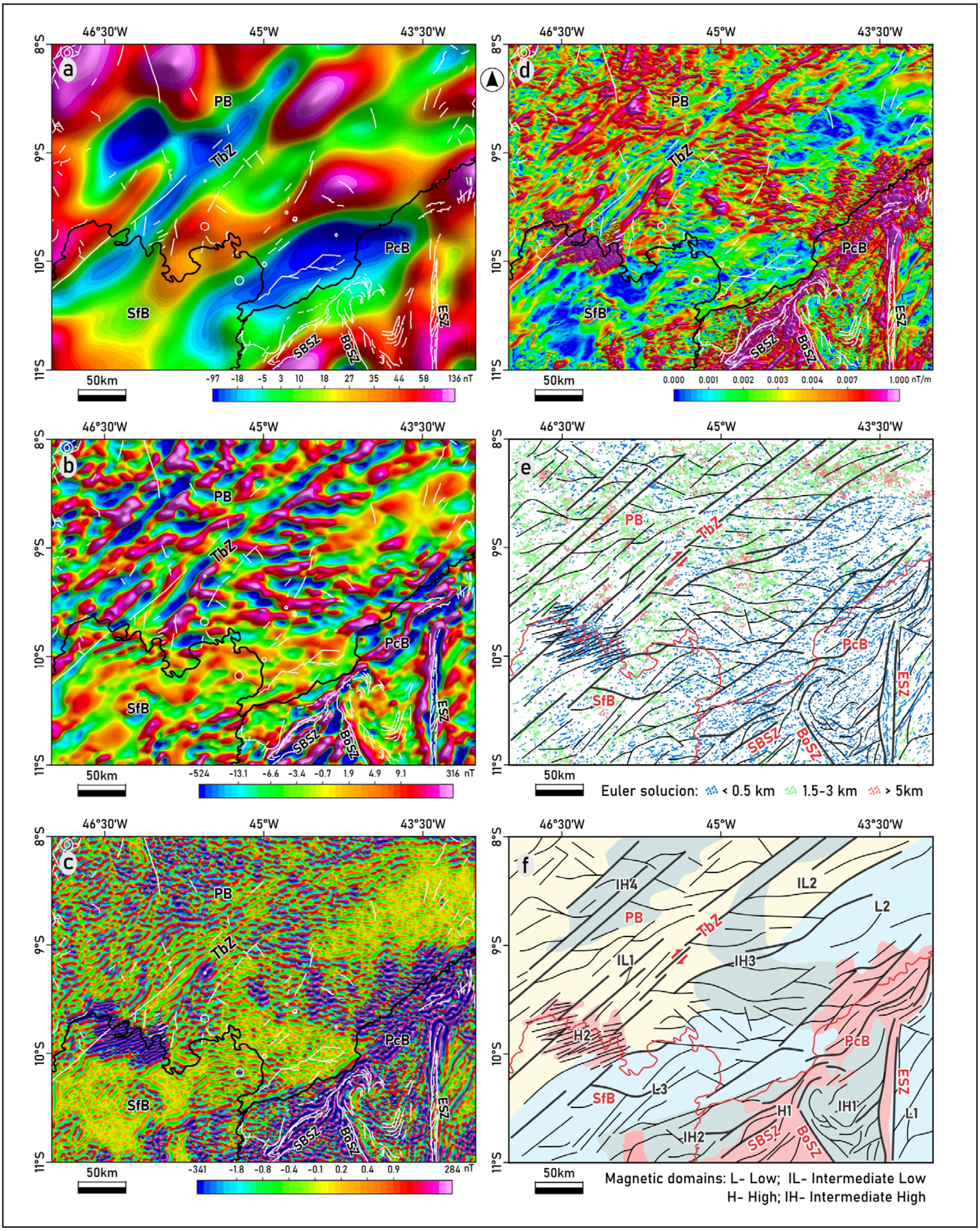

FIGURE 9. Pole-reduced magnetic anomaly maps processed for three depth levels from the application of the Matched-filter technique: 20 - 30 km (a), 5 - 8 km (b); 0.5 - 1 km (c). Map of the Total Gradient or analytical signal amplitude (d), map with the distribution of Euler solutions for depth estimation of magnetic sources and main magnetic alignments (e) and interpretative map of magnetic domains and lineaments along the study area (f).PB: Parnaíba Basin; SfB: Sanfranciscana Basin; PcB: Precambrian Basement. Brazilian structures and shear zones: SBSZ - Sebastião Barros; BoSZ - Boqueirão; ESZ - Estreito; TbZ - Transbrasiliano Zone. Magnetic anomalies are discussed in the text.

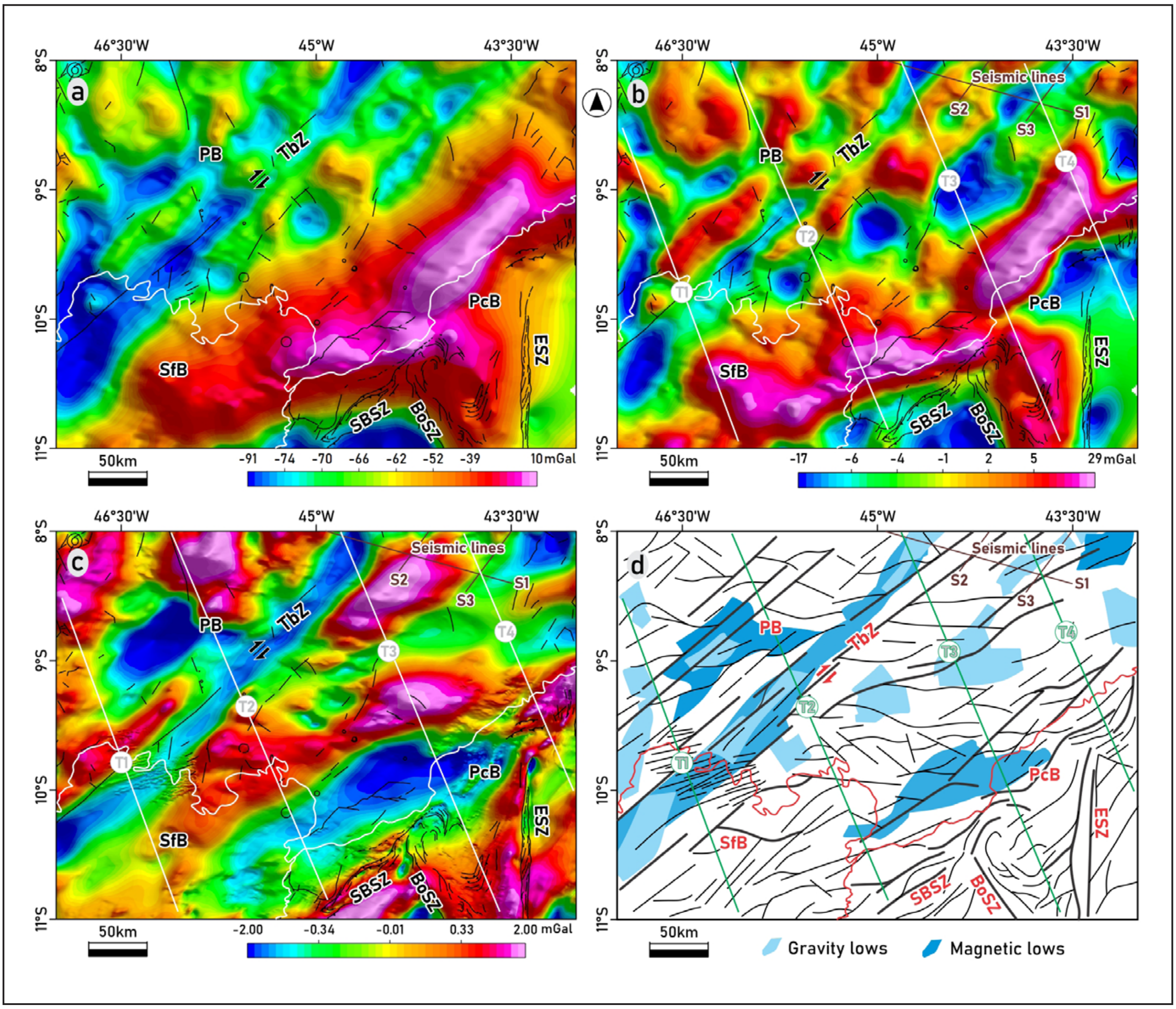

FIGURE 10. Maps of Bouguer gravity anomaly (a), residual gravity component (b) and pseudo-gravity (c) elaborated from the magnetic anomaly reduced to the pole. PB: Parnaíba Basin; SfB: Sanfranciscana Basin; PcB: Precambrian Basement. Brazilian structures and shear zones: SBSZ - Sebastião Barros; BoSZ - Boqueirão; ESZ - Estreito; TbZ - Transbrasiliano Zone. The gravity anomalies are discussed in the text.

From the residual gravity anomaly map (Figure 10b) it was possible to obtain information on the shallower portions of the upper crust, mainly the basement and the structural framework of the Parnaíba Basin. The residual anomaly highlights and delimits very well some features and structures present in the study area. The main one is the expressive gravity anomaly that occurs at the southern edge of the Parnaíba Basin and also affects the northern portion of the SfB (Figure 10b). Many authors interpret this high gravity gradient and its extension in the eastern portion of the basin as a paleosuture zone present along the margin belts located in the southern part of the Borborema Province and the northern portion of the SFC (Oliveira 2008; Carvalho et al. 2019; Vale et al. 2022; Porto et al. 2022). Another positive gravity anomaly occurs in the southeastern portion of the area and is bounded by the Boqueirão and Estreito shear zones (BoSZ and ESZ in Figure 10b). A justification for the high values of the gravity field in this area may be the presence of denser rocks associated with the Aulacogen Paramirim corridor (Figure 8b). It is noteworthy that on the west side, along the Sebastião Barros shear zone (SBSZ in Figure 10b), the Rio Preto Group and the Cristalândia do Piauí Complex present anomalies with negative values. This contrasting gravity pattern suggests the presence of two distinct crustal segments for this region of the basement. A similar pattern of gravity anomalies occurs in the extreme southeast and east of the basement region (east and north of ESZ in Figure 10b). These anomalies reflect the northern portion of the SFC, which crustal root should be thicker.

Gravity lows with a general NE-SW orientation may represent grabens or even basement features that have a lower density and consequently have a lower contribution to the gravity field at these locations. Conversely, the high gravity lines may represent horsts of the basement or belts that have denser rocks. The 2D seismic lines analyzed in this research (Figure 6), which have already been studied in other publications, do not reveal the presence of strong grabenform domains in the study area (Santos et al. 2018). This is a common feature, but it does not show continuity throughout the Parnaíba Basin.

To map grabens and rifts in the Parnaíba Basin, De Castro et al. (2016) successfully used the pseudo-gravity transformation tool and attributed the low gravity values to potential Cambrian-Ordovician grabens. This research used the same criteria, however the lithological characteristics of the basin substrate were also taken into account. The pseudo-gravity transformation map (Figure 10c) that was obtained presents important similarities with the residual gravity anomaly map (Figure 10b). The main ones are related to the internal framework of the Parnaíba Basin, which presents pseudo-gravity lows coincident with gravity lows (Figure 10d). Notably, these are regions more likely to contain grabenform features. However, an integrated assessment with the reflection seismic data (Figures 6 and 10d) shows that these lows demonstrated by the gravity signal do not always coincide with basement grabens. For example, along seismic section S1 (Figure 6) there is no indication of the presence of graben-like structures at the beginning of the section, even with the indication of gravity lows. Intuitively, these anomalies should mark basement features associated with the southern domain of the Borborema Province (Figures 8c and 10d). It is interesting to note that the pseudo-gravity and gravity high verified from these data in the central portion of seismic section S1 is coincident with a TbZ belt, in which a positive flower-type structure was interpreted. This configuration affects the rocks to a depth of approximately 4 km (Figure 6). This local feature is important, and does not exclude the possibility that other negative gravity anomalies coincide with basement gabrens. To try to avoid this effect a joint analysis with other geophysical methods and the modeling and inversion of magnetic and gravity data becomes indispensable for the investigation of this region.

4.3. Structural features along the Transbrasiliano Zone

Figure 11 presents a map of the main interpreted magnetic-structural lineaments for the TbZ region. This system covers an area approximately 400 km long and 80 to 100 km wide. The rosette diagram created based on the TbZ lineaments (Figure 11) shows a higher concentration of structures with a NE-SW preferential direction, more precisely between 50º and 60º, with subordinate lineaments along the N-S, E-W and NW-SE directions. This configuration is plausible with a rutile transcurrent system, of dextral kinematics and with a main displacement zone (PDZ in the Riedel diagram in Figure 11) of NE-SW direction. This scenario shows an indication of ENE-WSW direction for the axis of greatest stress - σ1. With this arrangement the development of normal faults and/or distensional fractures occurs perpendicular to the σ3 axis (approximately E-W) and the thrust or contractional faults should occur orthogonal to σ1 (Riedel diagram in Figure 11).

Swarms of dikes and sills of magmatic rocks of the Mosquito Formation outcrop in the southwest of the study area (Figure 3). Field magnetic and geological data suggest a much larger surface and/or subsurface area of occurrence for these rocks than is shown by current mapping. Mocitaba et al. (2017) revealed through magnetic data and statistical analysis, the magnetic domains related to the magmatic rocks of the Parnaíba Basin and demonstrated that the Mosquito Formation in the southern portion of the basin occupies an area of about 130 km long by 83 km wide.

Through the interpretation of magnetic lineaments and field analyses, it was possible to conclude that the formation and accommodation of these rocks took place along a preferential ENE-WSW axis, between 75º and 85º, longitudinal to σ1 (lineaments and blue rosette diagram in Figure 11). This shows that rupile reactivations of the TbZ in the Mesozoic were intense and important to the point of generating structures in deep regions of the crust and promoting the rise of magmatic material (4 in Figure 11), as well as the intrusion of kimberlitic bodies (2 and 5 in Figure 11). From a structural point of view, several features occurring along the TbZ are recognized, be they thrust faults (1 and 3 in Figure 11) and dextral kinematics (1 in Fig. 11). On a more regional scale, the reflection seismic data interpreted here and by Santos et al.

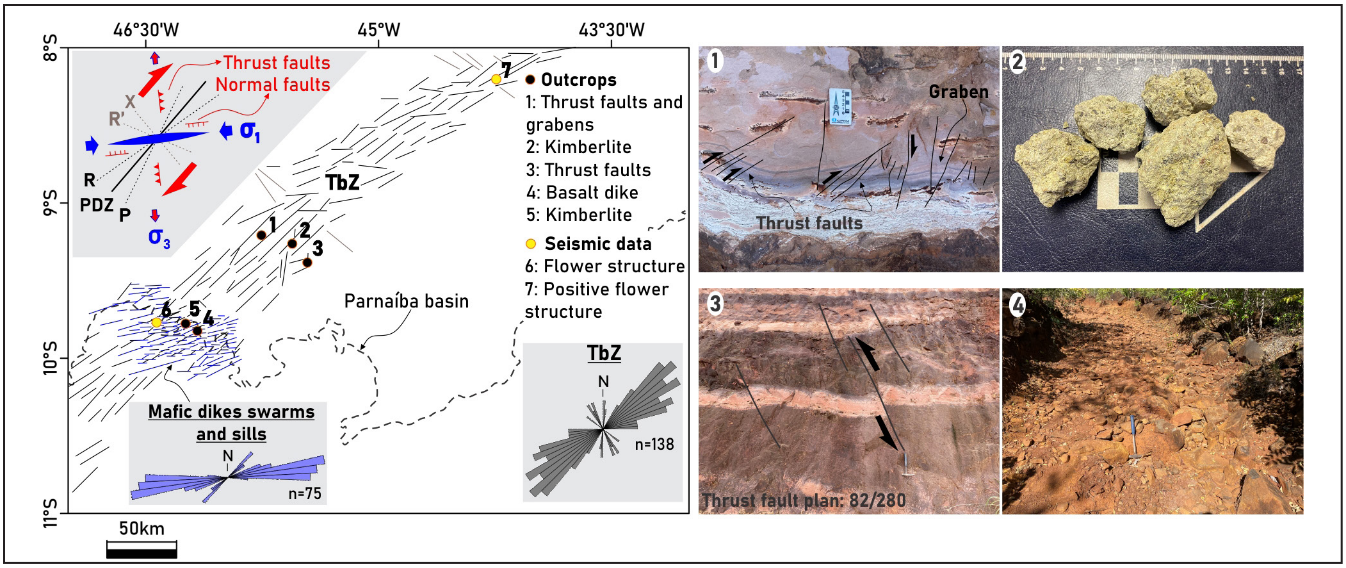

FIGURE 11. Map with the main magnetic lineaments along the Transbrasiliano Zone (TbZ). In the hatched parts are placed the Riedel diagram with its respective stress field within a rutile context of dextral transcurrence and the rosette diagrams with the preferential directions of the main magnetic-structural lineaments for the entire TbZ belt and for the region of magmatism in the Parnaíba Basin. PDZ is the main displacement plane, R, R', P and X are secondary structures associated with transcurrent tectonics. The dots on the map represent outcrops and samples of rocks and geological structures identified in seismic sections. On the right, photos of outcrops and rock samples collected in the study area (1 to 4).

(2018), show that along the TbZ there is a set of subvertical faults, with positive flower-like structures (S1 in Figure 6) and folds associated with sedimentary rock sequences (6 and 7 in Fig. 11). This compressive character must be related to more recent processes triggered by the inversion of the stress field (opposite to the opening scenario) in the basin region.

4.4. 3D inversion of the magnetization vector

The 3D inversion of the magnetization vector was promoted from a block with 221 x 167 horizontal cells (E-W and N-S, respectively) of 4000 km² each and 20 cells vertically. The mesh size varies with depth according to a geometric progression of ratio 1.08, and the shallowest cell is 500 m thick. The maximum depth of investigation for this model was 15 km. A link for extreme magnetization values was used using the weighted iterative inversion technique (IRI Focus, Ellis 2012). The iterations for IRI Focus were repeated twice, using both ends of the data (positive and negative).

Figure 12a shows the magnetic anomaly used as input in the data inversion process and its respective calculated magnetic anomaly (Figure12b). The model created represents a map with the magnetic susceptibility distribution for the study area (Figure 12c). A comparison between the observed and calculated anomalies along transects T1 to T4 shows a consistent fit of the data to the magnetic susceptibility model. However, there is a loss of high-frequency information, which meant that shallower bodies were suppressed from the model (Figure 12d). Only induced magnetization data were considered, as the inversion of the magnetization vector is not significantly affected by rocks with remnant magnetization (MacLeod and Ellis 2013).

In the basement region, it is evident the strong correlation of the rocks of the Rio Preto and Santo Onofre groups, through the Sebastião Barros and Estreito shear zones, respectively, with high magnetic susceptibility values (PcB, SBSZ and ESZ

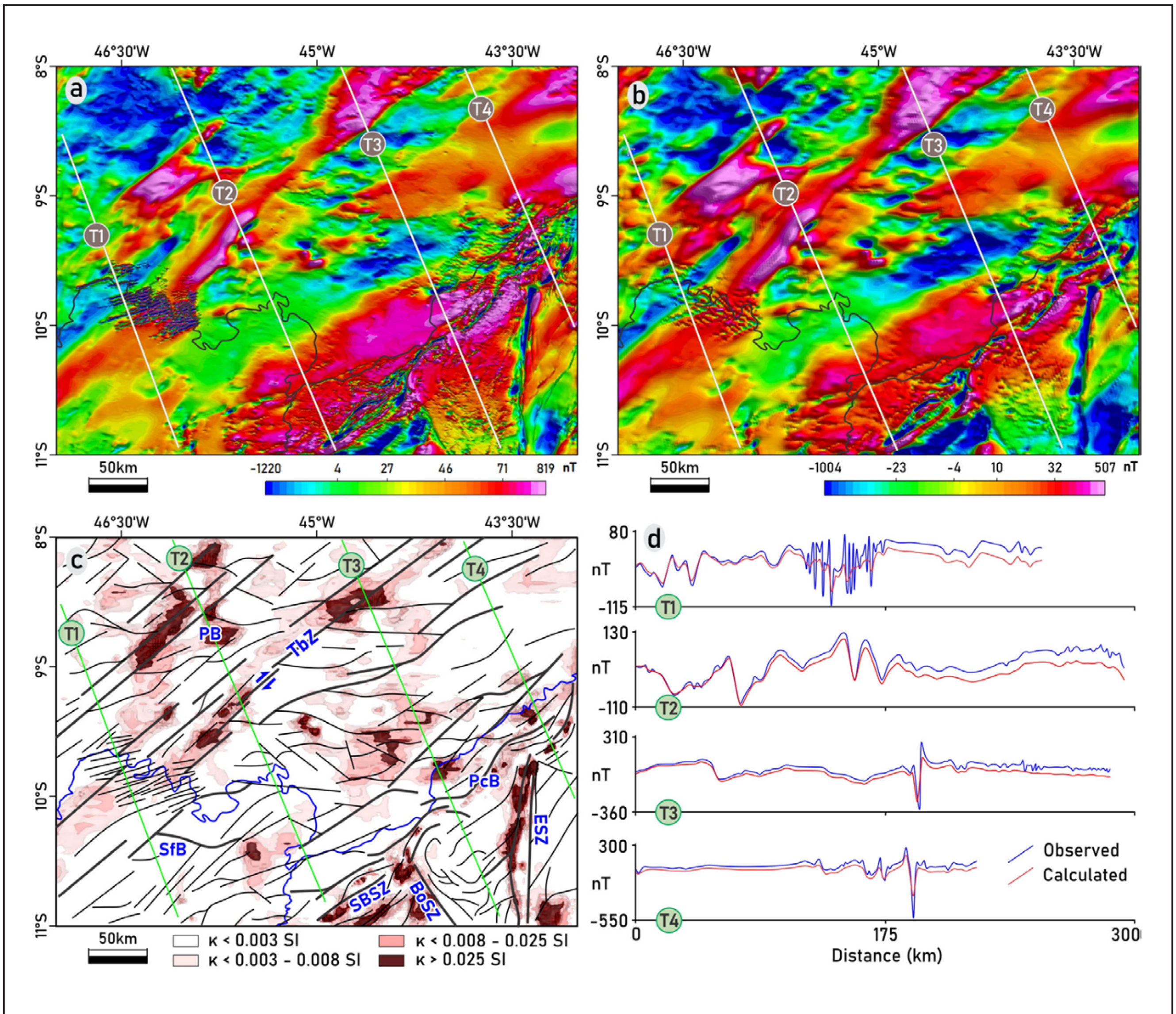

FIGURE 12. Observed magnetic anomaly used in the magnetization vector inversion process (a) and calculated magnetic anomaly (b). Map with the magnetic susceptibility distribution for the study area (c) and comparison between observed and calculated anomalies along transects T1 to T4 (d). PB: Parnaíba Basin; SfB: Sanfranciscana Basin; PcB: Precambrian Basement. Brazilian structures and shear zones: SBSZ - Sebastião Barros; BoSZ - Boqueirão; ESZ - Estreito; TbZ - Transbrasiliano Zone.

in Figure 12c). This pattern is related to the high content of magnetic minerals, which may also have formed during the action of the shearing processes, located at shallow depths along these units and are therefore important from an economic point of view. High values of magnetic susceptibility also occur along the contact between the basement rocks and the Parnaíba Basin (Figure 12c). In general, the Cristalândia do Piauí Complex has low magnetic susceptibility values, with irregular anomalous concentrations distributed near the contact of the Parnaíba and Sanfranciscana basins. A more representative anomaly was found in the central region of the study area and is associated with the northeastern part of what may be a fragment of the Brasilia Belt present along the structural framework of the southern edge of the Parnaíba Basin (Figures 9c and 12c).

When these results are compared with the geological data of the structural framework of the Parnaíba Basin, a good correlation between a belt with high magnetic susceptibility (> 0.01 SI) and the Transbrasiliano Zone (TbZ in Figure 12c) is evident. This corridor would be formed by the continuity of the rocks of the Goiás Magmatic Arc (GMA) and the Teresina Domain, north of the study area (Figure 9c). The higher concentrations of magnetic susceptibility in this region (> 0.025 SI) could be related to residual mafic-ultramafic bodies of the GMA, which are currently overlying the sedimentary rocks of the Parnaíba Basin, resulting from the subduction process that occurred during the Brasilian. A zone with higher values of magnetic susceptibility occurs in the northwestern part of the area, according to the main trend NNE-SSW and converges to the south following the GMA (Figure 12c). This anomalous feature would be related to the southern part of what is interpreted as the Barra do Corda Belt (Figure 9c).

4.5. 2.5D magnetic-gravity joint modeling

The crustal domains, geological units and rock types with the respective magnetic susceptibility and density values used in the joint modelling are summarized in Table 2. The errors considered for the fit between the observed and calculated values, based on the least squares method, ranged from 15.4% to 23.8% for the magnetic data and from 0.18% to 0.29% for the gravity data (curves for the magnetic and gravity signal in the upper part of Figure 13). The larger error for the magnetic data is due to the complexity of the magnetic field vector behavior and the presence of very shallow high-frequency sources in the magnetic signal (De Castro 2011; Pedrosa Jr. et al. 2017).

4.6. Internal architecture of the southern edge of the Parnaíba Basin

Figure 14 presents a synthesis of the results obtained by this research from the direct modeling and inversion of the data and the respective geological models that were elaborated on the transects on the southern edge of the Parnaíba Basin (Figures 13 and 14).

The T1 transect has a length of 283 km and was constructed in the westernmost portion of the study area (Figures 3 and 13). The final model shows a poorly moved basement relief, which density contrast between the basin and the basement units ranges from 140 to 233 kg/m^3. Some blocks of the basement show high density (HDB along T1, Figure 13), with lateral contrast of the order of 80 kg/m^3. Namely, the westernmost HDB may represent a crustal feature that would be associated with the boundary between the Grajaú Block and the East Araguaia and Barra do Corda belts (Figures 8c and 13). The central part of the T1 transect, between 100 and 170 km, is characterized by a high-frequency magnetic anomaly and a not very expressive gravity high further west. This pattern is characterized by sources related to dikes and sills of basalts and gabbros of the Mosquito Formation and a high density zone of the basement (HDB in Figure 13). The TbZ crosses this region and it is possible that the main conduits of magmatism are associated with movements of this feature that occurred during the Mesozoic. The MVI shows a strong magnetic susceptibility anomaly (> 0.04 SI) that could represent this indication (MVI model at the bottom of T1, Figure 13). In addition, the extension of the Goiás Magmatic Arc (GMA in Figure 8c), bounded by two continental paleosuture zones, further reinforces this scenario related to deeper structures in the upper crust (up to 15 km depth). The increase in gravity values and the less contrasting behavior of the magnetic field to the east are associated with a gentle rise of the basement, represented in this region by the northern Brasília Belt and the continuity of the Cristalândia do Piauí Complex (Figures 8c, 13 and 14). An HDB zone in this region may be associated with mafic-ultramafic rocks intruded within these units, while the higher density contrast in the basement region could represent contact with granitoid suites (Figures 13 and 14).

Immediately to the east, the 283 km-long T2 transect shows short-wavelength, high-amplitude magnetic anomalies, whereas the gravity anomaly is longer wavelength and softer in character (upper part of T2 transect in Figure 13). The region of the surface contact between the Parnaíba Basin and its basement is marked by two blocks of different densities. The eastern end, less dense, must represent low-grade metamorphic rocks of the Rio Preto Group, while the basement block immediately to the west, would be associated with a denser feature, belonging to the Cristalândia do Piauí Complex (Figures 8c, 13 and 14). The contact between the sedimentary cover and the basement is marked by a gentle increase in thickness in the succession of deposits in the NW direction, which maximum thickness is of the order of 1.8 km (well 1RB in Figure 7) (Figures 13 and 14). The Tbz is again represented by a block of the highest density basement (HDB in the central part of transect T2, Fig. 13), and which causes a small jump at the interface with the Serra Grande Group. The MVI well marks the contact between two blocks with different magnetic susceptibilities, which are separated by the TbZ. High values of magnetic susceptibility occur further west and are associated with the rocks of the Grajaú Block and the Barra do Corda Belt, which greater contrasts may represent paleo suture zones between these units and the Goiás Magmatic Arc (Figures 8c, 13 and 14).

The T3 transect is 350 km long and crosses the rocks of the Parnaíba Basin, supracrustal rocks of the Rio Preto Group and the basement belonging to the Cristalândia Complex of Piauí (Figures 3 and 13). The seismic interpretation shows that the contact between the sedimentary succession of the basin and the basement occurs at approximately 2 km depth (Figures 6 and 14). Keeping the proper proportions in relation to the wavelength, the magnetic and gravity anomalies

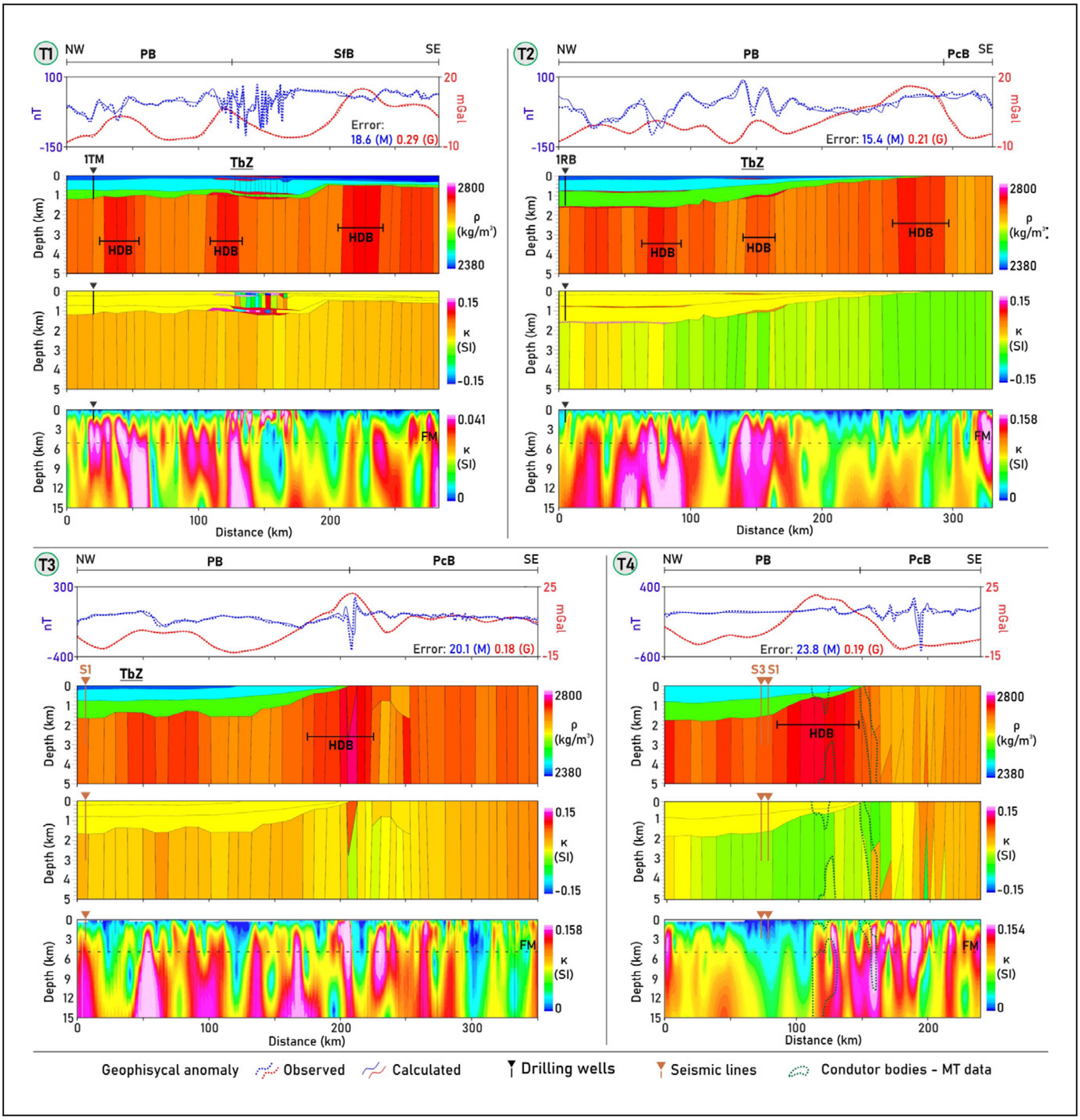

FIGURE 13. Result of modeling (FM) and magnetization vector inversion (MVI) along transects T1 to T4 (Figure 5). Below each of the observed and fitted magnetic and gravity signal curves are the models generated with the density and magnetic susceptibility distributions (FM and MVI). The fit of the curves for MVI is shown in Figure 12d. PB: Parnaíba Basin; SfB: Sanfranciscana Basin; PcB: Precambrian Basement; TbZ - Transbrasiliano Zone. HDB - High Density Basement. The interpreted seismic sections S1 and S2 are shown in Figure 6. The stratigraphic and geophysical profiling data of wells 1RB and 1TM are presented in Figure 7. Percentage error.

observed in the T3 transect show similar behavior, with emphasis on a high positive at the position of approximately 210 km (Figure 13). Notably, this feature reflects shallower to intermediate sources within the upper crust, with high values of magnetic susceptibility (> 0.12 SI), and density (HDB in transect T3 > 2750 kg/m³). This region also marks the surface contact between the Parnaíba Basin and the basement (PB and PcB in Figure 13). As observed in transects T1 and T2, a not very significant density contrast (< 50 kg/m³) again marks the TbZ at the beginning of transect T3 (Figure 13). Unlike the other sections, the contact west of the TbZ is not along the GMA rocks but at the TD (Figures 8c and 14). A not very prominent gravity high indicates that mafic-ultramafic rocks may occur along the TD at depths greater than 2 km (Figures 13 and 14). The extension of the Borborema Province units becomes more noticeable in transect T3, as the well-marked extension of the SZPe positioned at the contact between the northern and southern domains of the BP (PeSZ, NBP and SBP in Figures 8c and 14). Lateral variations of magnetic susceptibility and density, from 180 km away in this transect, are represented by gneissic-migmatitic rocks of the Cristalândia do Piauí Complex, and the set of denser and less dense blocks corresponds to mafic-ultramafic and granitoid suites, respectively (Figure 14). From 300 km away, where the rocks of the Rio Preto Group outcrop, there is a smooth increase in magnetic susceptibility values.

The T4 transect is approximately 240 km long (Figures 3, 13 and 14). On the surface, this section covers the rocks of the Serra Grande and Canindé groups and small windows of the basement (Figure 3). The interpretation of the seismic horizons in S1 and S3, based on the impedance and amplitude contrasts of the signal, revealed the main contacts between the units, and the thickness of the sedimentary succession which is of the order of 2 km (Figures 6 and 14). The magnetic and gravity signal curves in transect T4 are similar to what was obtained in transect T3. However, positive anomalies in both profiles are not coincident (see curves at T3 and T4 in Figure 13). This shift reinforces the idea that these anomalies correspond to different sources, one deeper, which has a long wavelength in the gravity signal, and another, shallower, with a shorter wavelength in the magnetic signal. In general, there is a significant compartmentalization in the physical models, while the western part shows lower values of magnetic susceptibility and higher density, the eastern part of the T4 transect shows an inverse pattern. The MVI highlights this compartmentalization well up to a depth of 15 km (Figure 13). A possible explanation for this pattern is associated with the magnetic and gravity sources in the region of the Cristalândia do Piauí Complex and the São Francisco Craton, which may contain mafic-ultramafic suites in shallower portions of the crust and a greater crustal thickness related to the craton region in the eastern part of the T4 transect (Figures 13 and 14). Magnetotelluric data revealed narrow, subvertical anomalies related to conductive bodies and/or structures in the crust (Romero et al. 2019). These features may represent intrusions of magmatic rocks of higher density and justify the expressive high gravity along the T4 transect (HDB in Figure 13), as well as structures of deeper character of the upper crust (conductive structures in MVI; T4 transect in Figure 13). The subsurface contact between the Parnaíba Basin and the basement is marked by density contrasts ranging from 150 to 350 kg/m^3, with a progressive thinning in the SE direction (Figures 13 and 14).

5. Conclusions

A model for the regional configuration of the structural framework of the southern edge of the Parnaíba Basin has been proposed. The 2.5D joint modeling of magnetic and gravity data and the 3D magnetization vector inversion of magnetic data allowed to identify in detail the internal architecture of the basin and the upper crust.

The results presented in this research corroborate with information addressed in previous works, as well as bring unprecedented aspects about the structural framework of the southern edge of the Parnaíba Basin, such as:

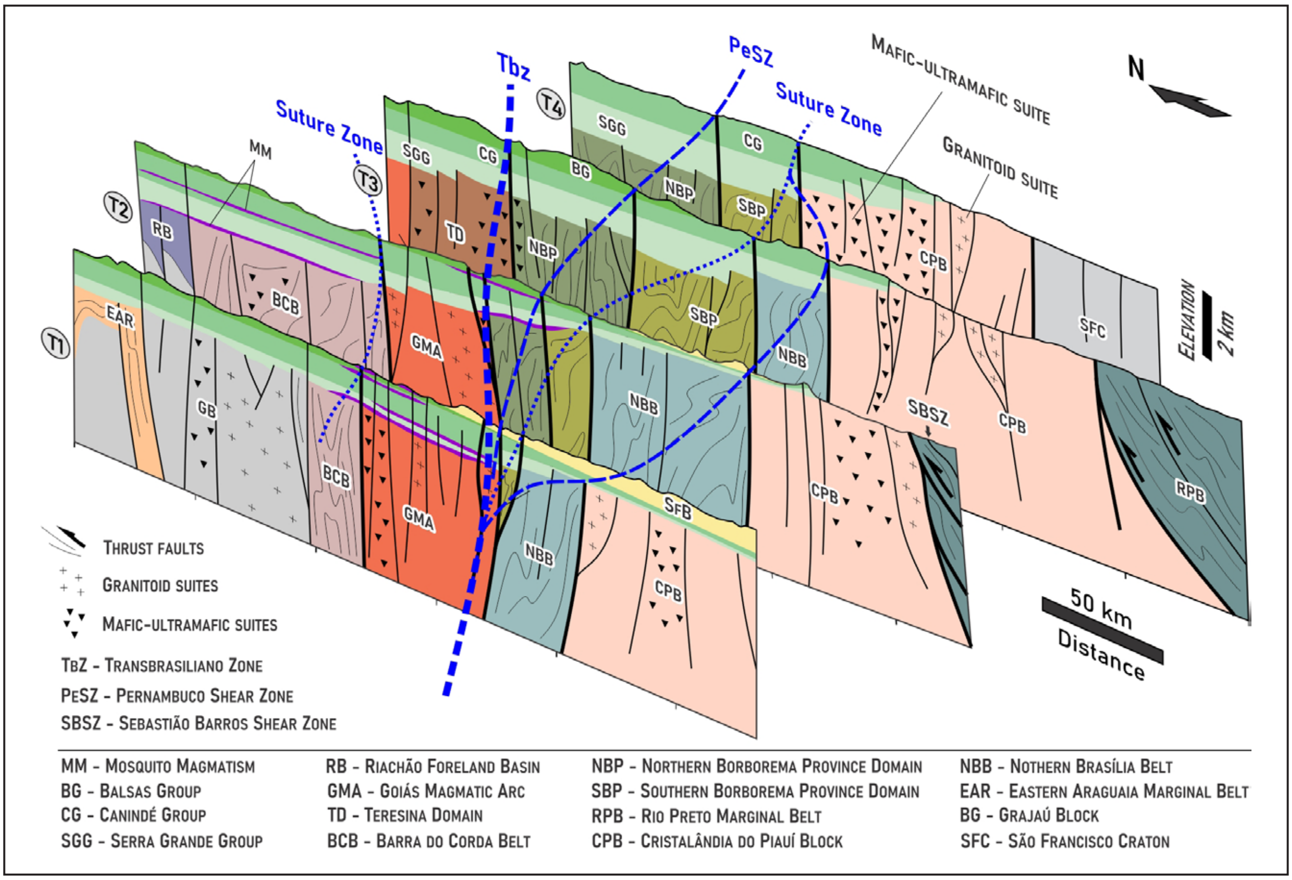

FIGURE 14. 3D block diagram summarizing the interpretation of the geotectonic configuration of the southern edge of the Parnaíba Basin in the region of the study area, constructed from the joint modelling and inversion of magnetic and gravity data. The results show the variations in thickness of the sedimentary cover of the basin, as well as the tectonostructural compartmentalization of the Precambrian basement characterized by heterogeneous pattern.

• Demonstration of the extension of several geological and tectonic structures from surrounding regions that constitute the internal framework of the basin, the most important of them, the Transbrasiliano Zone;

• Indication of the existence of continental paleosuture zones;

• Evidence that the tectonic framework of the basin is strongly influenced by the occurrence of reactivation events in the TbZ. This structural fabric produced important deformational processes that intensely modified most of the basement units, as well as the overlying sedimentary cover;

• Suggestion that the positioning of rifts and/or grabenform features is mostly related to sectors of TbZ weaknesses and structural discontinuities referring to the main shear zones of the Borborema Province;

• Absence of features associated with grabens or rifts along the transects, and the presence of gravity and pseudo-gravity lows is related to less dense tectonic units of the upper crust, such as granitic pockets and supracrustal sequences;

• Definition of four main magnetic domains with lineaments arranged in the main NE-SW direction. Three magnetic zones marked at different depths, between 20 km to 30 km, 5 km to 8 km and 0.5 km to 1 km, which allowed to establish the association of magnetic anomalies with shallow and deep crustal structures. They also show that the highest values of magnetic susceptibility in the subsurface are concentrated along the main structural discontinuities of the area;

• Indication that the variation of the thickness of the sedimentary succession of the basin shows a smooth thinning towards the basement, typical of sag-type intracratonic sedimentary basins. The maximum thickness of the basin along the transects is approximately 2 km.

• Suggestion that the action of the stress field during the opening of the Atlantic Ocean was responsible for the generation of rupile structures with deep crustal reach that promoted the ascent of basaltic rocks and the intrusion of kimberlitic bodies. And that these processes present potential related to the presence of economic, mineral and energy resources.

Acknowledgements

This work was supported by the Parnaíba Basin Project, developed in partnership with the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP), from where part of the geophysical data were kindly provided. This article was improved after the comments and suggestions of the reviewers, particularly Prof. Dr. David L. De Castro.

Authorship credits

Author	A	B	C	D	E	F
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ESAM			■	■		
MSF		■		■		

A - Study design/Conceptualization **B** - Investigation/Data acquisition
C - Data Interpretation/ Validation **D** - Writing
E - Review/Editing **F** - Supervision/Project administration

References

Arcanjo J.B.A., Braz Filho P.A. 2001. Curimatá: folha SC.23-Z-A, Corrente: folha SC.23-Y-B (parcial), Xique-Xique: folha SC.23-Z-B (parcial): estados da Bahia e do Piauí. Brasília, CPRM. 84 p. il. Escala 1:250.000. Programa Levantamentos Geológicos Básicos do Brasil - PLGB. Available on line at: https://rigeo.sgb.gov.br/handle/doc/8534.

Assis C.R.F., Moura C.A.V., Milhomem Neto J.M., Gorayeb P.S.S., Dias A.N.C. 2021. Zircon U-Pb geochronology and Lu-Hf isotope systematics of the Araguaia Belt basement rocks: Evidence of links with the southeastern Amazonian Craton, Brazil. Precambrian Research, 356, 106090. https://doi.org/10.1016/j.precamres.2020.106090

Barbosa J.S.F., Sabaté P. 2004. Archean and Paleoproterozoic crust of the São Francisco Craton, Bahia, Brazil: geodynamic features. Precambrian Research, 133, 1-27. https://doi.org/10.1016/j.precamres.2004.03.001

Barros R.A., Caxito F.A., Egydio-Silva M., Dantas E.L., Pinheiro M.A.P., Rodrigues J.B., Basei M.A.S., Virgens-Neto J.D., Freitas M.S. 2020. Archean and Paleoproterozoic crustal evolution and evidence for cryptic Paleoarchean-Hadean sources of the NW São Francisco Craton, Brazil: lithochemistry, geochronology, and isotope systematics of the Cristalândia do Piauí Block. Gondwana Research, 88, 268-295. https://doi.org/10.1016/j.gr.2020.07.004

Baksi A.K., Archibald D.A. 1997. Mesozoic igneous activity in the Maranhão province, northern Brazil: 40Ar/39Ar evidence for separate episodes of basaltic magmatism. Earth and Planetary Science Letters, 151(3-4), 139-153. https://doi.org/10.1016/S0012-821X(97)81844-4

Bellieni G., Macedo M.H.F., Petrini R., Piccirillo E.M., Cavazzini G., Comim-Chiaramonti P., Ernesto M., Macedo J.W.P., Martins G., Melfi A.J., Pacca I.G., de Min A. 1992. Evidence of magmatic activity related to Middle Jurassic and lower Cretaceous rifting from northeastern Brazil (Ceará-Mirim): K/Ar age, paleomagnetism, petrology and Sr–Nd isotope characteristics. Chemical Geology, 97(1-2), 9-32. https://doi.org/10.1016/0009-2541(92)90133-P

Blakely R.J. 1996. Potential theory in gravity and magnetic applications. Cambridge University Press, 441 p. https://doi.org/10.1017/CBO9780511549816

Briggs I.C. 1974. Machine contouring using minimum curvature. Geophysics, 39(1), 39-48. https://doi.org/10.1190/1.1440410

Brito Neves B.B., Fuck R.A. 2014. The basement of the South American platform: Half Laurentian (N-NW) + half Gondwanan (E-SE) domains. Precambrian Research, 244, 75-86. https://doi.org/10.1016/j.precamres.2013.09.020

Brito Neves B.B., Fuck R.A. Cordani U.G., Thomaz Filho A. 1984. Influence of basement structures on the evolution of the major sedimentary basins of Brazil. Journal of Geodynamics, 1, 495-510. https://doi.org/10.1016/0264-3707(84)90021-8

Campos J.E.G., Dardene M.A. 1997. Estratigrafia e sedimentação da Bacia Sanfranciscana: uma revisão. Revista Brasileira de Geociências, 27(3), 269-282. Available on line at: https://www.ppegeo.igc.usp.br/index.php/rbg/article/view/11291/10756

Caputo M.V., Lima E.C. 1984. Estratigrafia, idade e correlação do Grupo Serra Grande. In: Congresso Brasileiro de Geologia, 33, 740-753.

Carvalho C.D., Barros A.C.P., Rezende E.S., Brod E.R., Barros R.A., Pedrosa Jr. N.C., Silveira D.A. 2019. Áreas de Relevante Interesse Mineral – ARIM: Faixa Rio Preto, Estados do Piauí e Bahia. Informe de Recursos Minerais, Série Províncias Minerais do Brasil, Programa Geologia do Brasil, Avaliação de Recursos Minerais do Brasil, Teresina, 194 p. Available on line at: https://rigeo.sgb.gov.br/handle/doc/21415

Caxito F.A., Basto C.F., Santos L.C.M.L., Dantas E.L., Medeiros V.C., Dias T.G., Barrote V., Hagemann S., Alkmim A.R., Lana C. 2021. Neoproterozoic magmatic arc volcanism in the Borborema Province, NE Brazil: possible flare-ups and lulls and implications for western Gondwana assembly. Gondwana Research, 92, 1-25. https://doi.org/10.1016/j.gr.2020.11.015

Caxito F.A., Santos L.C.M.L., Ganade C.E., Bendaoud A., Fettous E.-H., Bouyo M.H. 2020. Toward an integrated model of geological evolution for NE Brazil-NW Africa: The Borborema Province and its connections to the Trans-Saharan (Benino-Nigerian and Tuareg shields) and Central African orogens. Brazilian Journal of Geology, 50(2) e20190122. https://doi.org/10.1590/2317-4889202020190122

Caxito F.A., Uhlein A., Morales L.F.G, Egydio-Silva M., Sanglard J.C.D., Dias T.G., Mendes M.C.O. 2014. Structural analysis of the Rio Preto fold belt (northwestern Bahia/southern Piauí), a doubly-vergent asymmetric fan developed during the Brasiliano Orogeny. Anais da Academia Brasileira de Ciencias, 86, 1101-1113. https://doi.org/10.1590/0001-3765201420130173

Cerri R.I., Warren L.V., Varejão F.G., Marconato A., Luvisotto G.L., Assine M.L. 2020. Unraveling the origin of the Parnaíba Basin: Testing the rift to sag hypothesis using a multi-proxy provenance analysis. Journal of South American Earth Sciences, 101, 102625. https://doi.org/10.1016/j.jsames.2020.102625

Cordani U.G., Brito Neves B.B., Thomaz Filho A. 2009. Estudo preliminar de integração do Pré-Cambriano com os eventos tectônicos das bacias sedimentares brasileiras (Atualização). Boletim de Geociências da Petrobras, 17(1), 205-219. Available on line at: https://repositorio.usp.br/item/002153382

Cordani U.G., Pimentel M.M., Araújo C.E.G., Fuck R.A. 2013. The significance of the Transbrasiliano-Kandi tectonic corridor for the amalgamation of West Gondwana, Brazilian Journal of Geology, 43, 583-597. https://doi.org/10.5327/Z2317-48892013000300012

Cunha A.R.A. 2011. Conversão em profundidade de dados migrados em tempo da Bacia do Parnaíba. Graduation work. Faculdade de Geofísica, Instituto de Geociências, Universidade Federal do Pará, Belém, 101 p. Available on line at: https://bdm.ufpa.br:8443/jspui/handle/prefix/1915

Cunha F.M.B. 1986. Evolução paleozoica da Bacia do Parnaíba e seu arcabouço tectônico. MSc Dissertation. Instituto de Geociências, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 107 p.

Daly M.C., Andrade V., Barousse C.A., Costa R., McDowell K., Piggott N., Poole A.J. 2014. Brasiliano crustal structure and the tectonic setting of the Parnaíba Basin of NE Brazil: results of a deep seismic reflection profile. Tectonics, 33(11), 2102-2120. https://doi.org/10.1002/2014TC003632

Daly M.C., Fuck R.A., Julià J., Macdonald D.I.M., Watts A.B. 2018. Cratonic basin formation: A case study of the Parnaíba Basin of Brazil. Geological Society, London, Special Publications, 472 (1), 1-15. https://doi.org/10.1144/SP472.20

Dalziel I.W.D. 1997. Neoproterozoic–Paleozoic geography and tectonics: review, hypothesis, environmental speculation. Geological Society of America Bulletin, 109, 16-42. http://dx.doi.org/10.1130/0016-7606(1997)109<0016:ONPGAT>2.3.CO;2

De Castro D.L. 2011. Gravity and magnetic joint modeling of the Potiguar rift basin (NE Brazil): basement control during Neocomian extension and deformation. Journal of South American Earth Sciences, 31, 186-198. https://doi.org/10.1016/j.jsames.2011.01.005

De Castro D.L., Bezerra F.H., Fuck R.A., Vidotti R.M. 2016. Geophysical evidence of pre-sag rifting and post-rifting fault reactivation in the Parnaíba Basin, Brazil. Solid Earth, 7(2), 529-548. https://doi.org/10.5194/se-7-529-2016

De Castro D.L., Fuck R.A., Phillips J.D., Vidotti R.M., Bezerra F.H.R. Dantas, E.L. 2014. Crustal structure beneath the Paleozoic Parnaíba Basin revealed by airborne gravity and magnetic data, Brazil. Tectonophysics, 614, 128-145. https://doi.org/10.1016/j.tecto.2013.12.009

De Castro D.L., Oliveira D.C., Hollanda M.H.B.M. 2018. Geostatistical interplay between geophysical and geochemical data: mapping litho-structural assemblages of Mesozoic Igneous activities in the Parnaíba Basin (NE Brazil). Surv Geophys, 39, 683-713. https://doi.org/10.1007/s10712-018-9463-5

Ellis R.G. 2012. Iterative reweighted inversion. Geosoft Technical Note. Toronto: Geosoft, 2012. Available on line at: http://www.geosoft.com/products/voxi-earth-modelling/iterative reweighting-inversion / (accessed on 10 January 2022).

Ellis R.G., Wet B., Macleod I.N. 2012. Inversion of magnetic data from remanent and induced sources. In: Annual Australian Society of Exploration Geophysicists Conference and Exhibition, Expanded Abstracts, 22, 1-4. https://doi.org/10.1071/ASEG2012ab117

Góes A.M.O., Feijó F.J. 1994. Bacia do Parnaíba. Boletim de Geociências da Petrobras, 8, 57-67.

Góes A.M.O., Souza J.M.P. Teixeira L.B. 1990. Estágio exploratório e perspectivas petrolíferas da Bacia do Parnaíba. Boletim de Geociências da Petrobras, 4(1), 55-64.

Heilbron M., Cordani U.G., Alkmim F.F. 2016. The São Francisco Craton and its margins. In: Heilbron M., Cordani U.G., Alkmim F.F. (eds.). São Francisco Craton, Eastern Brazil, regional geology reviews. Springer, 3-13. https://doi.org/10.1007/978-3-319-01715-0_1

Hodel F., Trindade R.I.F., Macouin M., Meira V.T., Dantas E.L., Paixão, M.A.P., Rospabé M., Castro M.P., Queiroga G.N., Alkmim A.R., Lana C.C. 2019. A Neoproterozoic hyper-extended margin associated with Rodinia's demise and Gondwana's build-up: the Araguaia Belt, central Brazil. Gondwana Research, 66, 43-62. https://doi.org/10.1016/j.gr.2018.08.010

Lima F.G.F., Jardim de Sá E.F. 2017. Controle estrutural da borda sudeste da Bacia do Parnaíba, Nordeste do Brasil: relação com eventos geodinâmicos no Gondwana. Geologia USP, Série Científica, 17(3), 3-21. http://dx.doi.org/10.11606/issn.2316-9095.v17-125909

Loureiro H.S.C., Lima E.S., Macedo E.P., Silveira F.V., Bahiense I.C., Arcanjo J.B.A., Moraes Filho J.C., Neves J.P., Guimarães J.T., Teixeira L.R., Abram M.B., Santos R.A., Melo R.C. 2008. Projeto Barra - Oliveira dos Brejinhos: estado da Bahia. Programa Recursos Minerais do Brasil. Salvador, CPRM/CBPM, 156 p. Available on line at: https://rigeo.sgb.gov.br/handle/doc/21793

MacLeod, I.N., Ellis, R. 2016. Quantitative magnetization vector inversion. In: Geophysical Conference & Exhibition, 25, 1-5. https://doi.org/10.1071/ASEG2016ab115

MacLeod, I.N., Ellis, R.G. 2013. Magnetic vector inversion, a simple approach to the challenge of varying direction of rock magnetization. In: Proceedings of the ASEG Forum on the Application of Remanent Magnetization, Expanded Abstracts, 1-4.

Merle R., Marzoli A., Bertrand H., Reisberg L., Verati C., Zimmermann C., Chiaradia M., Bellieni G., Ernesto M. 2011. $^{40}Ar/^{39}Ar$ ages and Sr–Nd–Pb–Os geochemistry of CAMP tholeiites from Western Maranhão basin (NE Brazil). Lithos, 122, 137-151. https://doi.org/10.1016/j.lithos.2010.12.010

Mocitaba L.S.R., De Castro D.L., Oliveira D.C. 2017. Cartografia geofísica regional do magmatismo mesozoico na Bacia do Parnaíba. Geologia USP, Série Científica, 17(2), 169-192. https://doi.org/10.11606/issn.2316-9095.v17-455

Nabighian M.N. 1984. Toward a three-dimensional automatic interpretation of potential field data via generalized Hilbert transforms: fundamental relations. Geophysics 49(6), 780-786. https://doi.org/10.1190/1.1441706

Oliveira R.G. 2008. Arcabouço geofísico, isostasia e causas do magmatismo Cenozóico da Província Borborema e de sua margem continental (Nordeste do Brasil). PhD Thesis, Universidade Federal do Rio Grande do Norte, Natal, 411 p. Available on line at: https://repositorio.ufrn.br/handle/123456789/18344

Pedrosa Jr. N.C., Vidotti R.M., Fuck R.A., Castelo Branco R.M.G., Almeida A.R., Silva N.C.V., Braga L.R. 2017. Architecture of the intracontinental Jaibaras Rift, Brazil, based on geophysical data. Journal of South American Earth Sciences, 74, 27-40. http://dx.doi.org/10.1016/j.jsames.2016.12.012

Pedrosa Jr. N.C., Vidotti R.M., Fuck R.A., Leopoldino Oliveira K.M., Castelo Branco R.M. G. 2015. Structural framework of the Jaibaras Rift, Brazil, based on geophysical data. Journal of South American Earth Sciences, 58, 318-334. https://doi.org/10.1016/j.jsames.2014.07.005

Phillips J.D. 2001. Designing matched bandpass and azimuthal filters for the separation of potential-field anomalies by source region and source type. In: Geophysical Conference and Exhibition, 15, 1-4. https://doi.org/10.1071/ASEG2001ab110

Porto A., Carvalho C., Lima C., Heilbron M., Caxito F., La Terra E., Fontes S.L. 2022. The Neoproterozoic basement of the Parnaíba Basin (NE Brazil) from combined geophysical-geological analysis: a missing piece of the western Gondwana puzzle. Precambrian Research, 379, 106784. https://doi.org/10.1016/j.precamres.2022.106784

Porto A., Daly M.C., La Terra E., Fontes S. 2018. The pre-Silurian Riachão basin: a new perspective on the basement of the Parnaíba Basin, NE Brazil. Geological Society, Special Publications, 472(1), 127-145. https://doi.org/10.1144/SP472.2

Prado F.S., Vasconcelos A.M. 1991. Barra do Bonito: folha SC.24-V-A-VI: estados do Piauí e Bahia. Escala 1:100.000. Programa Levantamento Geológicos Básicos do Brasil. Brasília, CPRM, 160 p. Available on line at: https://rigeo.sgb.gov.br/handle/doc/8494

Queiroz D.S. 2019. Transecta sísmica N-S através do depocentro da Bacia do Parnaíba: Aproximação por função do receptor e CCP. MSc Dissertation, Programa de Pós-Graduação em Geologia, Instituto de Geociências, Universidade de Brasília, Brasília, 66 p. Available on line at: https://repositorio.unb.br/handle/10482/35202

Rocha N.S., Fontes S.L., La Terra E.F., Fuck R.A. 2019. Lithosphere structures of the Parnaíba Basin and adjacent provinces revealed by deep magnetotelluric imaging. Journal of South American Earth Sciences, 92, 1-11. https://doi.org/10.1016/j.jsames.2019.02.020

Romero G., La Terra E.F., Panetto L.P., Fontes S.L. 2019. Upper crustal structures of the southeast edge of Parnaiba basin using

3D magnetotelluric data imaging. Journal of South American Earth Sciences, 96, 102392. https://doi.org/10.1016/j.jsames.2019.102392

Romero-Beltran G., Tupinambá M., Panetto L.P., La Terra E.F., Fontes S.L. 2022. Resistivity imaging from magnetotelluric soundings of the Rio Preto Belt (NE Brazil): The role of lateral variations in the Precambrian basement on the evolution of phanerozoic basins. Journal of South American Earth Sciences, 116, 103780. https://doi.org/10.1016/j.jsames.2022.103780

Saltus R.W., Blakely R.J. 2011. Unique geologic insights from "non-unique" gravity and magnetic interpretation. Geological Society of America, 21(12), 4-10. https://doi.org/10.1130/G136A.1

Santos H.O.S., Jardim de Sá E.F., Silva F.C.A., Antunes A.F. 2018. Reativações pós-silurianas do Lineamento Transbrasiliano na porção sul da Bacia do Parnaíba. Geologia USP, Série Científica, 18(2), 71-86. https://doi.org/10.11606/issn.2316-9095.v18-134712

Schiffer C., de Lima M.V.A.G., Soares J.E.P., Stephenson R., de Araújo V.C.M., Lima F.T., Rocha F.A.S., Trindade C.R., Fuck R.A. 2021. Vp/Vs ratios in the Parnaíba Basin from joint active-passive seismic analysis: implications for continental amalgamation and basin formation. Tectonophysics, 801, 228715. https://doi.org/10.1016/j.tecto.2020.228715

Soares J.E.P., Stephenson R., Fuck R.A., Lima M.V.A.G., Araújo V.C.M., Lima F.T., Rocha F.A.S., Trindade C.R. 2018. Structure of the crust and upper mantle beneath the Parnaíba Basin, Brazil, from wide-angle reflection–refraction data. Geological Society, London, Special Publications, 472, 67-82. https://doi.org/10.1144/SP472.9

Solon F.F., Fontes S.L., La Terra E.F. 2018. Electrical conductivity structure across the Parnaíba Basin, NE Brazil. Geological Society, Special Publications, 472(1), 109-126. https://doi.org/10.1144/SP472.19

Spector A., Grant F.S. 1970. Statistical models for interpreting aeromagnetic data. Geophysics, 35(2), 293-302. https://doi.org/10.1190/1.1440092

Swain C.J. 1976. A FORTRAN IV program for interpolating irregularly spaced data using the difference equations for minimum curvature. Computers e Geosciences, 1(4), 231-240. https://doi.org/10.1016/0098-3004(76)90071-6

Talwani M., Heirtzler J.R. 1964. Computation of magnetic anomalies caused by 2D bodies of arbitrary shape. In: Parks, G.A. (Ed.), Computers in the Mineral Industries, Part 1, Geological Sciences, Stanford University Publications, 9, 464-480.

Talwani M., Worel J.L., Landisman M. 1959. Rapid gravity computations for 2D bodies with application to the Mendocino submarine fracture zone. Journal of Geophysical Research, 64, 49-59. https://doi.org/10.1029/JZ064i001p00049

Tavares A.C., De Castro D.L., Clausen O.R., Bezerra F.H.R., Sousa M.O.L., Gomes M. P., Vital H., Oliveira D.C. 2022. Continental-scale structural heritage from rift extension to postrift inversion: implications for the central Brazilian Equatorial Margin evolution. Tectonophysics 837, 229446. https://doi.org/10.1016/j.tecto.2022.229446

Thompson D.T. 1982. EULDPH: a new technique for making computer assisted depth estimates from magnetic data. Geophysics 47(1), 31-37. https://doi.org/10.1190/1.1441278

Tozer B., Watts A.B., Daly M.C. 2017. Crustal structure, gravity anomalies, and subsidence history of the Parnaíba cratonic basin, Northeast Brazil. Journal of Geophysical Research: Solid Earth, 122 (7), 5591-5621. https://doi.org/10.1002/2017JB014348

Uchôa Filho E.C., Vale J.A.R., Basto C.F., Freitas M.S., Silveira D.A., Pedrosa Junior N.C., Menezes R.G., Mota E.S.A. 2019. Áreas de relevante interesse mineral (ARIM): faixas marginais da Borda Noroeste do Cráton São Francisco: área faixa Riacho do Pontal: estado de Piauí e Pernambuco., Informe de Recursos Minerais, Série Províncias Minerais do Brasil, 27. Teresina, CPRM, 216 p. Available on line at: https://rigeo.sgb.gov.br/handle/doc/21427

Vale J.A.R., Carvalho C.D., Pedrosa Junior N.C., Freitas M.S., Mota E.S.A., Silveira D.A., Barros A.C.P. 2022. Áreas de relevante interesse mineral (ARIM): avaliação do potencial mineral da região de São Raimundo Nonato. Informe de Recursos Minerais, Série Províncias Minerais do Brasil, 36. Teresina, CPRM, 260 p. Available on line at: https://rigeo.sgb.gov.br/handle/doc/20336

Vaz P.T., Rezende N.G.A.M., Wanderley Filho J.R., Travassos W.A.S. 2007. Bacia do Parnaíba. Boletim de Geociências da Petrobras, 15, 253-263.

Won I.J., Bevis M. 1987. Computing the gravitational and magnetic anomalies due to a polygon: algorithms and Fortran subroutines. Geophysics, 52(2), 137-241. https://doi.org/10.1190/1.1442298

Zalán P.V. 1991. Influence of Pre-Andean orogenies on the Paleozoic intracratonic basins of South America. In: IV Simpósio Bolivariano, Exploración Petrolera em las Cuencas Subandinas, Bogotá, 1, 7.