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Geophysical characterization and tectonic insights of the Western Meridional Borborema Province in the Northeastern Region of Brazil

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ABSTRACT

The Western Meridional Borborema Province (MBP) and the northern part of the São Francisco Craton (SFC) experienced significant tectonic events during the Neoproterozoic era. However, their geological history remains incompletely understood due to the absence of comprehensive studies on the deep crustal structure situated in the Western MBP. This study aims to explore the boundaries of the crustal blocks between the western MBP and the northern SFC, with the objective of enhancing the understanding and contributing to the reconstruction of their geological history. To achieve the defined objectives, we utilized, gravimetric, magnetic, and elevation data. Lateral extensions were determined by anomalous magnetic field transformations, while source depths were calculated using the An-Euler method. The results revealed source depths between 1.0 km and above 5.0 km, with a structural index of 1.0 to 3.0, are observed in both the SFC and the Borborema cross-section, as well as west of the Sergipano Belt. These different structural indices represent magnetic source geometries, which can vary from a dyke, an intrusive body or a localized mineral concentration. These results were used as a priori information in the 3D forward modeling of the crust to obtain the density contrast distribution in the subsurface. The results indicate that the Riacho do Pontal Belt has a crustal thickness of 38.2 km, which is thinner compared to the values ranging from 41.6 km to the north of the SFC with values ranging from 41.6 km.

Keywords: Magnetic Data; 3D Gravity Modeling; Crustal Structure.

Caracterización geofísica y tectónica de la provincia de Borborema sudoccidental, en el nordeste de Brasil

RESUMEN

La Provincia Meridional Borborema Occidental (PMB) y la parte norte del Cratón de São Francisco (CSF) experimentaron eventos tectónicos significativos durante la era Neoproterozoica. Sin embargo, su historia geológica sigue siendo incompletamente comprendida debido a la ausencia de estudios integrales sobre la estructura crustal profunda situada en la Provincia Meridional Borborema Occidental. Este estudio tiene como objetivo explorar los límites de los bloques crustales entre la PMB occidental y el CSF norte, con el objetivo de mejorar la comprensión y contribuir a la reconstrucción de su historia geológica. Para lograr los objetivos definidos, utilizamos datos geofísicos, gravimétricos, magnéticos y de elevación. Las extensiones laterales fueron determinadas por transformaciones anómalas del campo magnético, mientras que las profundidades de las fuentes se calcularon utilizando el método An-Euler. Los resultados revelaron profundidades de fuentes entre 1.0 km y por encima de 5.0 km, con un índice estructural de 1.0 a 3.0, que se observan tanto en el CSF como en la sección transversal de Borborema, así como al oeste del Cinturón Sergipano. Estos resultados se utilizaron como información a priori en la modelización 3D directa de la corteza para obtener la distribución del contraste de densidad en el subsuelo. Los resultados de espesor crustal indican adelgazamiento crustal en el Cinturón Riacho do Pontal a 38.2 km, en comparación con el norte del CSF con valores que oscilan entre 41.6 km.

Palabras Clave: datos magnéticos; modelado gravitacional 3D; estructura de la corteza terrestre

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1. Introduction

The Borborema Province is a crucial geological complex subject to significant tectonic phenomena involving several crustal blocks in northeastern Brazil. However, the comprehensive understanding of its tectonic history remains uncertain due to the lack of consistent studies on the deep crustal structure of the crystalline basement in the study area, situated to the west of the Southern Borborema Province.

The delimitation of the boundaries between crustal blocks, the investigation of their origins and the precise definition of crustal limits continue to be issues that are susceptible to uncertainty within the geoscientific context. An illustrative example of this challenge is the demarcation between the SFC basement's northern segment and the Borborema Southern Province's western region (MBP), characterized by overlaps. The complexity inherent in this demarcation results from the overlapping of tectonic events, intricate geological structures, substantial deformations of significant magnitude and extensive magmatic occurrences, the result of geotectonic compartmentalization during the collisional and post-collisional phases of the Brasiliana/Pan-African Orogeny.

The tectonic occurrences in the MBP have been substantiated by Caxito et al. (2016, 2017, 2020), who conducted investigations into these events, ultimately affirming the existence of a comprehensive Wilson cycle within the Riacho do Pontal orogen. Several significant geophysical studies have contributed to elucidating this phenomenon, including the works of Oliveira (2008), Santos et al. (2014), Correa et al. (2016), and Oliveira and Medeiros (2018). Geophysical data, encompassing gravity and magnetic measurements, have been employed to acquire insights into crustal structures, facilitating an enhanced comprehension of the geotectonic processes in the Borborema Province during the Neoproterozoic era.

Several researchers have elaborated on this geotectonic framework by interpreting lateral variations in density and magnetization and estimating elastic parameters. In the work by Santos et al. (2014), it was found that in the southern domain of the province (Sergipano Belt and Pernambuco-Alagoas Block), the crust is heterogeneous, while the upper mantle is abnormally conductive. The crust and mantle are predominantly homogeneous and resistive when entering the transverse domain (Alto Moxotó Terrain). This difference in the heterogeneity of the crust is interpreted as being mainly due to the extensional activity that took place in the Cretaceous period. These efforts aim to identify the underlying factors responsible for the uplift of the Borborema Province. Such endeavors bolster magnetic and gravity data utilization within the academic sphere, facilitating a deeper understanding and precise delineation of the geological terrain (Sampaio et al., 2017; Silva and Sampaio, 2017).

This article offers valuable insights into the western MBP and the northern SFC basement. This is achieved by leveraging the processing outcomes and interpretations of pre-existing gravity and aeromagnetic data through 3D forward modeling.

As a result, this study has successfully estimated the depth of the uppermost sources, identified and characterized the boundaries of anomalous subsurface bodies, and delineated lineations and shear zones. Additionally, it has elucidated variations in subsurface crustal density, which were previously insufficiently documented in the studied region.

To accomplish these objectives, a comprehensive range of geophysical techniques was employed, including the application of the total magnetic intensity (TMI) map, the analytical signal of tilt angle (ASTA), tilt angle (TDR) analysis, vertical derivative (Dz), and the An-Euler method. The resulting findings offer valuable insights into the geotectonic configuration and its associated boundaries, thereby enhancing our understanding of the crustal structure within the context of Gondwana formation.

In addition, a three-dimensional (3D) gravimetric modeling approach was adopted, which involves the creation of a subsurface model that represents the distribution of density contrast. This methodology aims to better understand the architecture of the earth's crust in the study area. The choice of this technique is based on its ability to allow the interpretation of potential data, integrating synergistically with geological information and average density values.

2. Geological context

The Borborema Province exhibits a subdivision into three distinct tectonic subprovinces, namely the Northern, Transversal (central), and Southern subprovinces. Moreover, the primary demarcation lines that delineate these domains are represented by the Patos and Pernambuco Shear Zones, as established by prior research (Brito Neves et al., 2000; Medeiros, 2004; Oliveira, 2008; Caxito et al., 2017; Lima, 2018).

The geological history of the Borborema Province is a complex narrative of tectonic and magmatic processes stretching from the Archean to the Paleoproterozoic with signatures of granitoids of Neoproterozoic origin. This has resulted in a diverse series of geological features and structures that reveal the evolution of the province in various stages. The bedrock of the province is composed of an Archean complex, surrounded by fragments of Paleoproterozoic orthogneiss. Within this Archaean complex, the São José do Campestre Massif stands out, which includes rocks from 3.45 - 2.70 Ga (Dantas et al., 2013).

Subsequent periods (1000-960 Ma) witnessed the formation of volcanic and plutonic rocks during the Meso-Neoproterozoic transition, notably during the Cariris Velhos Orogeny (Santos et al., 2024). These events shaped the geological composition of the province and added layers of complexity to its history, the Augen-Gnaisse Suite of Afeição (Caxito et al., 2014).

A later and crucial phase in the evolution of the province was the complete tectonic cycle known as Pan-African/Brazilian, occurring between 900 and 500 Ma (Caxito et al., 2017; Caxito et al., 2022). This cycle involved intricate processes such as the creation of oceanic crust, subduction, the formation of magmatic arcs and, eventually, continental collision. These activities left a lasting mark on the province, characterized by intense tectonic and metamorphic phenomena. The culmination of this geological saga is seen in the formation of magmatic intrusions, particularly notable in the Pernambuco-Alagoas domain and in the northeastern region of the province (Cruz et al., 2014). These intrusions, resulting from the intense igneous activity associated with the Pan-African/Brazilian, significantly influence the density and magnetism characteristics of the province's basement, adding another layer of complexity to its geological history.

The Southern Subprovince encompasses the Meridional Borborema Province (MBP), representing a significant tectonic segment within the Borborema Province. The hypothesis proposed for the geological evolution of the Borborema Province suggests that its crust evolved through a series of classic Wilson cycles (Caxito et al., 2022; Caxito et al., 2016; Araujo et al., 2014). These cycles involved crustal rifting, the opening and closing of oceans, the establishment of subduction zones and, eventually, continental collision.

This geological evolution results from the Neoproterozoic orogenic event that transpired between South America and West Africa during the formation of the supercontinent Gondwana. During this period, major continental blocks, including the Amazonian Craton, São Francisco-Congo, and São Luis-West Africa, converged and interacted as part of the Brazilian/Pan-African orogeny in the Neoproterozoic. Various researchers have extensively studied and documented this complex geological history (Oliveira, 1998, 2008; da Silva et al., 2008; Silva et al., 2011; Araujo et al., 2014; Lima et al., 2018; Passos et al., 2022). The MBP is located within a specific tectonic context: i) To the northwest, it is partially overlain by the Paraíba Basin; ii) To the north, it is delimited by the Pernambuco Lineament; iii) To the south, it extends to the SFC basement, encompassing the Riacho do Pontal Belt, the Pernambuco-Alagoas Domain and the Sergipano Belt (Fig. 1).

In addition, the eastern portion of the MBP contains geotectonic domains that form the foundation of the Sergipe-Alagoas Basin. These domains include, from north to south, Canindé, Poço Redondo-Marancó, Macururé, Vaza Barris and Estância, delimited by Neoproterozoic shear zones: Macururé, Belo Monte-Jeremoabo, São Miguel do Aleixo and Itaporanga (Oliveira et al., 2010; Passos et al., 2022).

Lima et al. (2018) conducted a study on metasedimentary and metavolcanic rocks of the Araticum Complex, associating their formation with an oceanic volcanic arc environment linked to the Brasiliana Orogeny. Later, Passos et al. (2022) carried out research on amphibolites, interpreting them as part of the Canindé Domain and relating them to the Neoproterozoic arc and retroarc system on the continental margin of the Borborema Province.

These interpretations obtained by Silva et al. (1999), Oliveira et al. (2010), Lima et al. (2018), and Passos et al. (2022) support the existence of an oceanic basin between the Pernambuco-Alagoas domain and the SFC. This interpretation reinforces the model of extensional tectonics, which would have resulted in the opening of the ocean between the São Francisco-Congo Craton and the Pernambuco-Alagoas domain, followed by later collisional tectonics between 680-540 Ma with intrusion of gabbroic bodies into the geotectonic domains that make up the Sergipano Belt , strengthening the existence of a Wilson Classic Cycle model (Silva et al., 1999; Oliveira et al., 2010; Lima et al., 2018; Passos et al., 2022).

To the south of the MBP lies the Salvador-Esplanada-Boquim domain, which is associated with the SFC basement, as documented by Santos and Medeiros (1999).

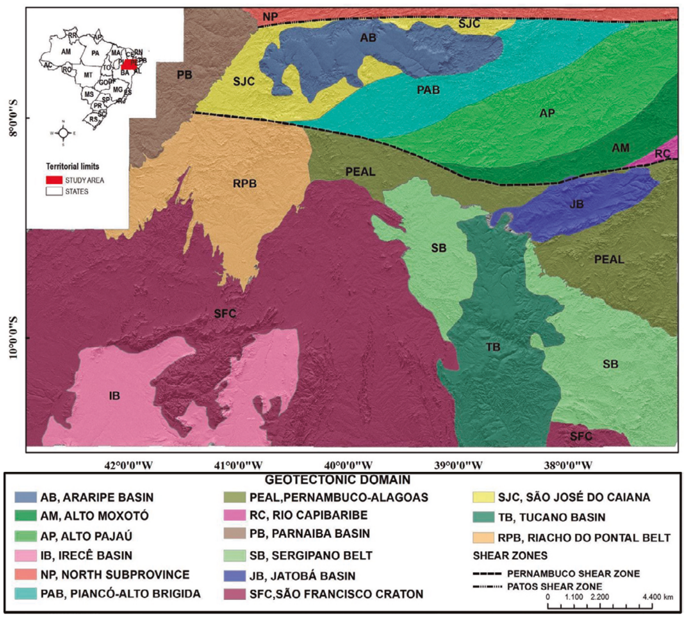

Figure 1. Map of the tectonic domains of the Southern and Transversal Borborema Province.

The Riacho do Pontal Belt, a significant geological feature in the region, exhibits various geological characteristics, including sedimentary, metamorphic, and structural features. This belt is typically subdivided into three main zones: The Internal Zone, the Central Zone, and the External Zone. The geological attributes of each zone have been extensively studied and documented by various researchers, such as Oliveira (1998, 2008), Caxito (2013), Oliveira and Medeiros (2018).

Starting with the Internal Zone, this area is characterized by geological complexes like the Paulistana Complex, Santa Filomena Complex, and Morro Branco, along with igneous suites such as Serra da Aldeia and Rajada. It features granite intrusions, metavolcanic-sedimentary rocks from the Paulistana, Santa Filomena, and Morro Branco Complexes, and additional igneous suites like Afeição, Rajada, Serra da Aldeia, Brejo Seco, and São Francisco de Assis (Caxito, 2013; Caxito et al., 2016, 2017). Moving on to the Central Zone, the prominent geological feature here is the Monte Orebe Complex. This zone encompasses a mix of volcanic and sedimentary associations. Researchers like Brito de Brito Neves et al. (2015) have attributed this unit to transforming tholeiitic metabasalts with low potassium content, possibly indicating an oceanic floor or island arch environment.

Finally, the External Zone, situated at the southernmost part of the belt, includes the Casa Nova Complex and is characterized by a foreland folding strip. Geophysical studies conducted by Oliveira (1998, 2008) in this region suggest low supracrustals and nappe thickness structures associated with the SFC. Overall, these detailed geological investigations and categorizations provide valuable insights into the complex geological history and structural evolution of the Riacho do Pontal Belt and its surrounding areas.

The Pernambuco-Alagoas Domain is characterized by a diverse composition, including high-grade terrains, Archean and Paleoproterozoic formations, metavolcanic-sedimentary rocks, and granitoids (Neves and da Silva Filho, 2019). Within this domain, two significant metamorphic complexes are prominent: the Belém do São Francisco Complex, primarily composed of granite and granodioritic orthogneisses, and the Cabrobó Complex, which comprises a variety of metamorphic rocks, including schist, gneiss, metagraywacke, quartzite, marble, calc-silicate rocks, and amphibolite (Lima, 2018).

The Sergipe Belt, situated within the Southern Sub-Province of the MBP, borders to the north with the Pernambuco-Alagoas Domain and to the south with the (SFC). This belt signifies a collisional phase during the Brasiliano orogenic event. It is characterized by a supracrustal sequence of metamorphosed rocks displaying characteristics of a passive continental margin and a retro-arc basin (Foreland), as detailed by Oliveira et al. (2015).

The (SFC) constitutes a significant geotectonic entity within the South American Platform. It encompasses Proterozoic and Phanerozoic units, including the São Francisco Basin, the Paramirim Group, and a portion of the Tucano-Jatobá rift. The boundaries of the SFC are delineated by geological belts formed during the Brasiliano orogeny, including the Brasilia Belt to the west and the Rio Preto Belt to the northwest. Additionally, the Riacho do Pontal Belt is located in the northern part of Craton (Barbosa and Sabaté, 2004).

The works of Allard and Hurst (1969), Cordani et al. (1973), and Trompette (1997) have highlighted the presence of metasedimentary rocks in the Vaza-Barris group located in the southern part of the Sergipano Belt, drawing connections to the Ndjole Belt in northern Gabon, Africa. A hypothesis also suggests a significant collision event, supported by geophysical anomalies within the Borborema Province, inferring that it may represent a suture zone between ancient continental blocks (Oliveira, 2008). This orogenic activity is observed in the Riacho do Pontal Belt, characterized by five stages of geodynamic evolution and interpreted as a complete Wilson Cycle (Caxito et al., 2016).

3. Data and numerical method

3.1. Geophysical data

We used different geophysical data sets: aeromagnetic and gravimetric data, geoid anomaly and topography. The aeromagnetic data used in this study were obtained from geophysical aerial survey projects conducted and provided by CPRM - Brazilian Geological Survey and CBPM - Companhia Bahia de Pesquisa Mineral. These projects include the following: Serra de Itiúba (Project 1023), Southern Edge of the Parnaiba Basin (Project 1027), and Pernambuco-Piauí (Project 1067). Additionally, the data in GeoTIFF files format were provided by CBPM, originating from the Aerogeophysical Projects: Campo Alegre de Lourdes-Mortugaba (Project 29), Center North Bahia (Project 36), Senhor do Bonfim (Project 23), Campo Formoso (Project 22), and Rio Seco-Andorinha (Project 27). These datasets were acquired with flight line spacing ranging from 500 meters to 2 kilometers and control lines spanning 2 to 5 kilometers. The data obtained from these banks, to which we had access, had already been corrected by the IGRF. Data processing and analysis were done using the Geosoft Oasis Montaj software version 9.9. The regular grid, containing all the aeromagnetic projects, was generated using the Grid Stitching tool using the Suture Method, available in the same version of the software. This technique is used to join several grids together.

Furthermore, gravity data in the form of Bouguer anomalies, geoid anomalies, and topographic data were acquired from the International Center for Global Earth Models (ICGEM) database. The EGM2008 Model (European Improved Gravity Model of the Earth) developed by Pavlis et al. (2012) was utilized for Bouguer anomaly calculations. The geoid anomaly data were derived from the GECO global gravity model introduced by Gilardoni et al. (2016). Topography data were extracted from the ETOPO1 global relief model, accessible through the National Geospatial-Intelligence Agency — Earth Gravitational Model (NGA, 2008) platform, with an arc resolution of 1×1 minute.

3.2. Data processing

The magnetic data set was interpolated using the bidirectional method with the 125x125-meter interpolation cell. The initial step involved constructing a power spectrum using data about the anomalous magnetic field. Spectral analysis, rooted in the principles of the Fourier Transform, was employed to estimate the average depth of subsurface bodies. This estimation was based on the spatial correlation between field intensity and wave number, as detailed by Spector and Grant (1970).

Through this spectral analysis, we determined a cut-off point (wave number) that delineates the boundary between shallow and deep sources and their respective depths. Following establishing this cut-off point, we applied an upward continuation filter to the magnetic data. The cut-off point was set at 0.266 km, with a wave number of 0.70 cycles per kilometer (cycles/km), obtained from the radial power spectrum. This filter attenuated high-frequency components associated with shallow sources while accentuating or amplifying signals originating from deeper sources, corresponding to the bedrock.

After the spectral analysis, we enhanced our geophysical analysis by implementing two additional techniques: the vertical derivative (DZ) method, as detailed by Blakely (1996) and Cooper and Cowan (2004), and the slope angle analytical signal (ASTA) approach, as described by Miller and Singh (1994). These methods were important in delineating geological structures and identifying geophysical lineaments within the area of interest. Moreover, we determined the preferred orientations of these geophysical lineaments using rosette diagrams, which provided valuable insights into the structural characteristics of the region.

Together with the spectral analysis, we also used the Nabighian (1972) An-Euler and Analytical Signal (ASA) deconvolution technique to emphasize and position the amplitude peaks in the causative sources in order to get an idea of the geometry of the geotectonic domains in the study area. These windows were based on geotectonic domains such as the SFC's western portion, the SFC's northern southern portion, the Sergipano Belt, the Transversal Subprovince, and part of the Southern Borborema. The structural index assigned was from 1 to 3. The structural index (SI) = 0 was not used, as it would indicate that the anomaly remained constant, regardless of the distance from the source. This set allowed us to determine the horizontal location and depth of the magnetic sources. This set of parameters and techniques allowed us to determine the horizontal location and depth of the magnetic sources. The results of the An-Euler deconvolution technique were incorporated as a priori information in our crustal modeling efforts.

To estimate the depth of the Moho, we leveraged topography and geoid anomaly data, employing the methodology established by Fullea et al. (2007). This approach integrates various data, like topography, geoid anomaly, and thermal analysis, to determine crust (Moho) and lithosphere thickness, along with the average density of the lithospheric mantle. To enhance modeling accuracy, we applied a low-pass filter in the frequency domain to the topography data, eliminating high-frequency effects that could introduce noise, specifically filtering out wavelengths shorter than 72.80 kilometers. Similarly, the geoid data underwent low-pass filtering, removing the first 10 harmonic coefficients in the geoid anomaly data. The resulting Moho depth was used as the initial crustal parameter in the gravimetric modeling of the Borborema Meridional West province, alongside the Bouguer anomaly data (Fig. 2).

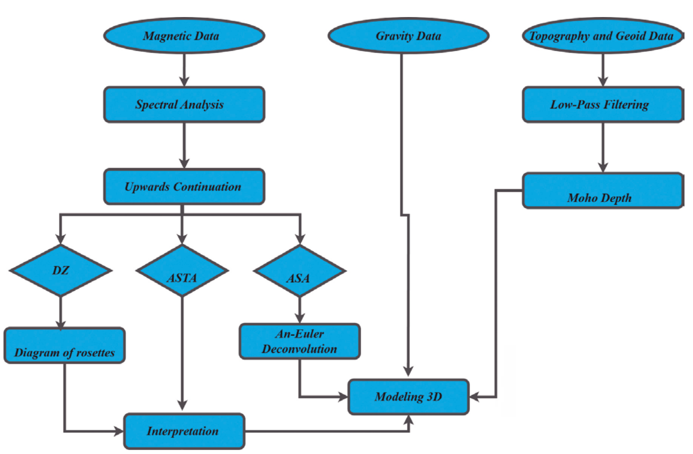

Figure 2. Workflow.

3.3. 3D Forward Modeling: Crust modeling

Integrating potential data with geological information enables the development of models capable of measuring physical parameters like density and calculating gravitational effects resulting from homogeneous sources. For crustal modeling in this study, we employed IGMAS+ (Interactive Gravity and Magnetic Application System). IGMAS+ is a software program that utilizes an initial model geometry consisting of parallel vertical sections, and the modeling process involves triangular polyhedral meshes (see Fig. 3). In addition to its capabilities in gravimetric modeling, IGMAS+ can generate susceptibility models from magnetic field data, as detailed by Schmidt and Götze (1998), Götze and Lahmeyer (1988), and Götze (2013).

The numerical algorithm that forms the basis of IGMAS+ is based on the methods pioneered by Götze (1976); Götze and Lahmeyer (1988); Götze (2013). This algorithm allows for determining the vertical component of gravitational attraction arising from a polyhedron, along with the computation of gravity gradients, utilizing Poisson´s ratio.

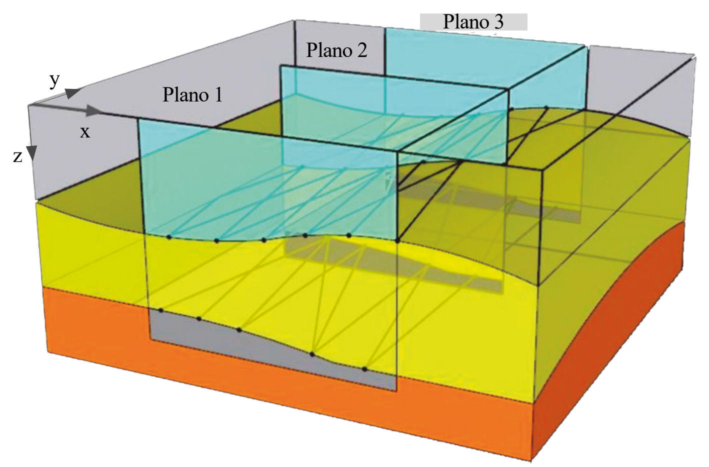

Figure 3. Using Bouguer anomaly data to model the crust: Illustration of the initial definition of the layer model. The first layer, represented by orange, corresponds to the Moho. The layers represented by yellow and grey correspond to the crust. Source: adapted from the Gómez Dacal, 2012.

4. Results

The primary outcomes from the techniques encompass the Detection of Geotectonic Body Edges. The methods employed allowed for identifying and delineating the boundaries of geotectonic bodies within the study area. These findings contribute to a comprehensive understanding of the geological structure. The Determination of Source Depths through the An-Euler Solutions technique provided valuable insights into the depths of magnetic sources within the region. This information aids in characterizing subsurface geological features and their spatial distribution.

The Estimation of Moho Thickness: Through the integration of topography and geoid anomaly data, along with the application of specialized methodologies, the thickness of the Moho, which marks the boundary between the Earth's crust and mantle, was estimated. This knowledge enhances our comprehension of the Earth's subsurface structure. Utilizing these outcomes, a density contrast model for the study area was constructed (Table A1). This model is a valuable tool for further geological and geophysical investigations, enabling a more detailed and accurate representation of the subsurface properties and structures within the region.

Figure 4 depicts the magnetic field map after applying upward continuation. The upward continuation has been applied for distance of 266 meters was utilized in this process, a value determined through radial power spectrum analysis of the total magnetic field data. The main goal of this procedure was to highlight significant geological structures at deeper levels while minimizing the impact of shallower magnetic sources.

We applied the first-order vertical derivative to the continuous magnetic field data (Fig.5) to accentuate geological sources and shallow structures, including lineaments. Subsequently, to gain insights into the orientation of these lineaments, we constructed a rosette diagram (Fig. 5) that illustrates the geological framework. The results indicate a predominant alignment of geophysical lineaments in the E-W direction, extending potentially up to ENE. Conversely, within the SFC, there is a prevalence of N-S (north-south) lineaments, in contrast to the southern and transversal Borborema Province, which exhibits NE-SW-oriented lineaments (Fig. 5).

These findings collectively suggest that the studied area is characterized by predominantly shallow structures and geological lineaments, with their orientations varying between different regions, as delineated by the rosette diagram.

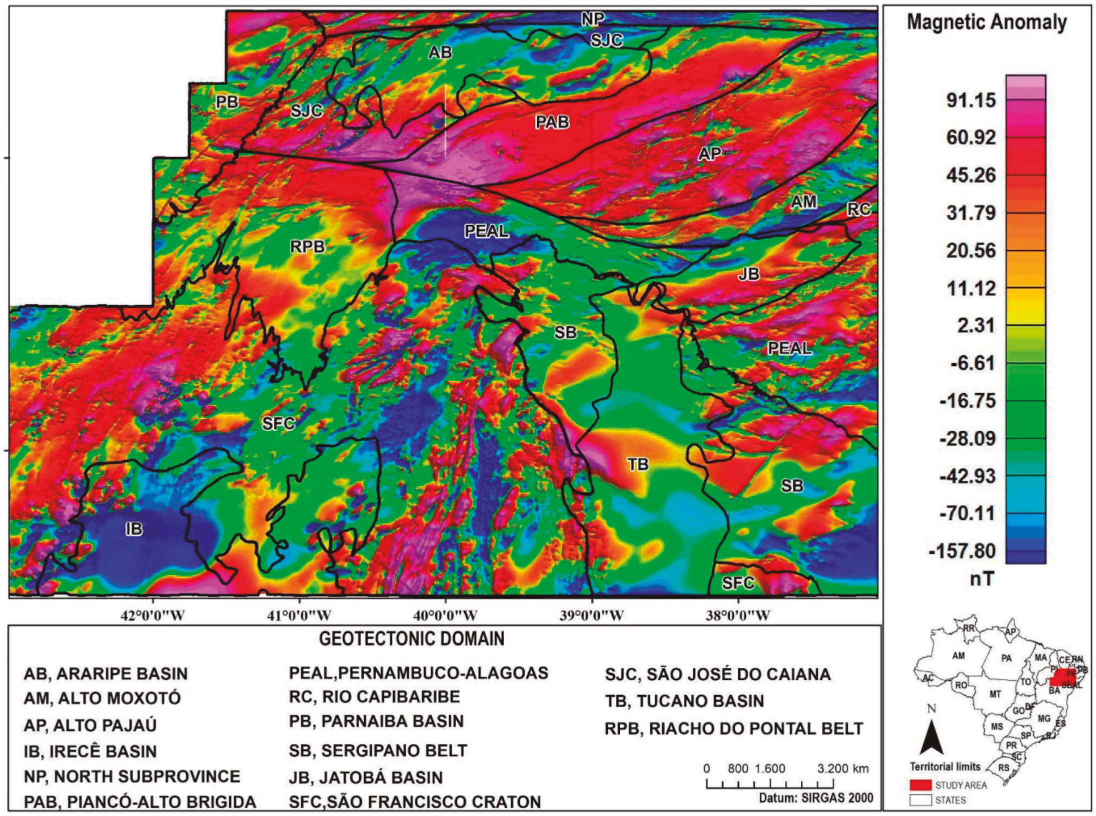

Figure 4. Magnetic map with continuation upwards at 0.266 km.

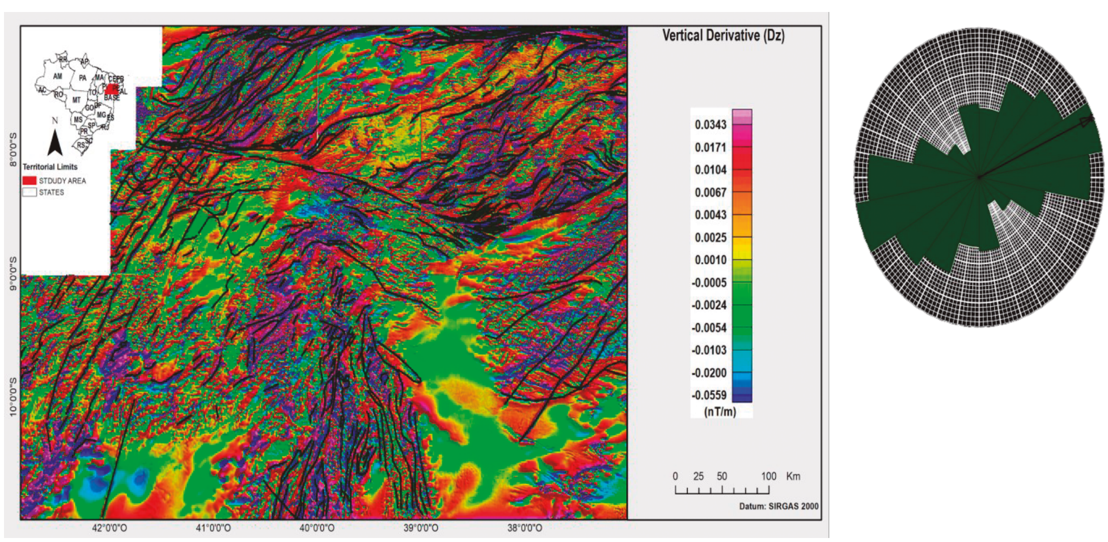

Figure 5. Magnetic structures interpreted from the maps of the Vertical Derivative (Dz) with the continuation of the anomalous magnetic field at 0.266 km with their respective diagram of rosettes corresponding to the extracted lines.

Figure 6 displays the ASTA (slope angle analytical signal) map, which effectively delineates the boundaries of existing geotectonic domains within the study area. From this analysis, several noteworthy observations can be made: a) The Maximum Values to the East of the Transversal Borborema Province; b) Minimum Values to the North of the SFC.

The ASTA map shows maximum values mainly located east of the Transversal Borborema Province, covering regions such as São José do Caiana, Alto Pajaú , Alto Moxotó, and Rio Capibaribe. It's worth noting exceptions in the Araripe Basin and Piancó-Alto Brígida.

On the other hand, the map depicts minimum ASTA values situated north of the SFC, with heightened intensity noted in areas such as IB (possibly referring to the Irecê Basin), TB (potentially the Tucano Basin), southeast Sergipano Belt (likely representing a southeastern portion of the Sergipe-Alagoas Basin), and JB (potentially referring to the Jatobá Basin).

The map distinctly outlines the positioning and interface between the Riacho do Pontal Belt and the northern boundary of the SFC. This demarcation is characterized by a unique contour that conforms to the geological structure of the Craton.

Moreover, the map effectively illustrates the geometry and contact points of the Tucano, Jatobá, and Irecê Basins in the filtered magnetic data, enhancing our understanding of their spatial relationships within the study area.

These observations derived from the ASTA map significantly contribute to our understanding of the region's geological and geophysical characteristics, aiding in identifying key geological features and their boundaries.

Figure 7 provides valuable insights into the depths of magnetic sources within the study area, as determined through the An-Euler deconvolution method. Key observations from the clustering of these solutions are as follows. The concentration of depths reveals that the most solutions are within depth ranges spanning from less than 1 kilometer to 5 kilometers. This concentration suggests that the causative magnetic sources have relatively shallow thicknesses, characterized by structural indices of 1 (indicative of dikes or sills), and 2 or 3 (representing cylinders or spheres) (Fig. 7).

Regarding spatial distribution, the shallow magnetic sources are primarily concentrated within the SFC to the east of the Sergipano Belt. However, a smaller number of such sources are also observed in the transversal part of the Borborema Province, attributed to the presence of high-amplitude magnetic sources in these regions. Notably, there is depth variability with sources less than 1 kilometer and greater than 5 kilometers, exhibiting structural indices ranging from 1 to 3. These sources are distributed within the SFC, the transversal segment of the Borborema Province, and to the west of the Sergipano Belt (Fig. 7).

These findings shed light on the heterogeneous nature of magnetic sources in the study area, with varying depths and structural characteristics. Understanding the distribution and depths of these sources is crucial for unraveling the geological and geophysical complexities of the region.

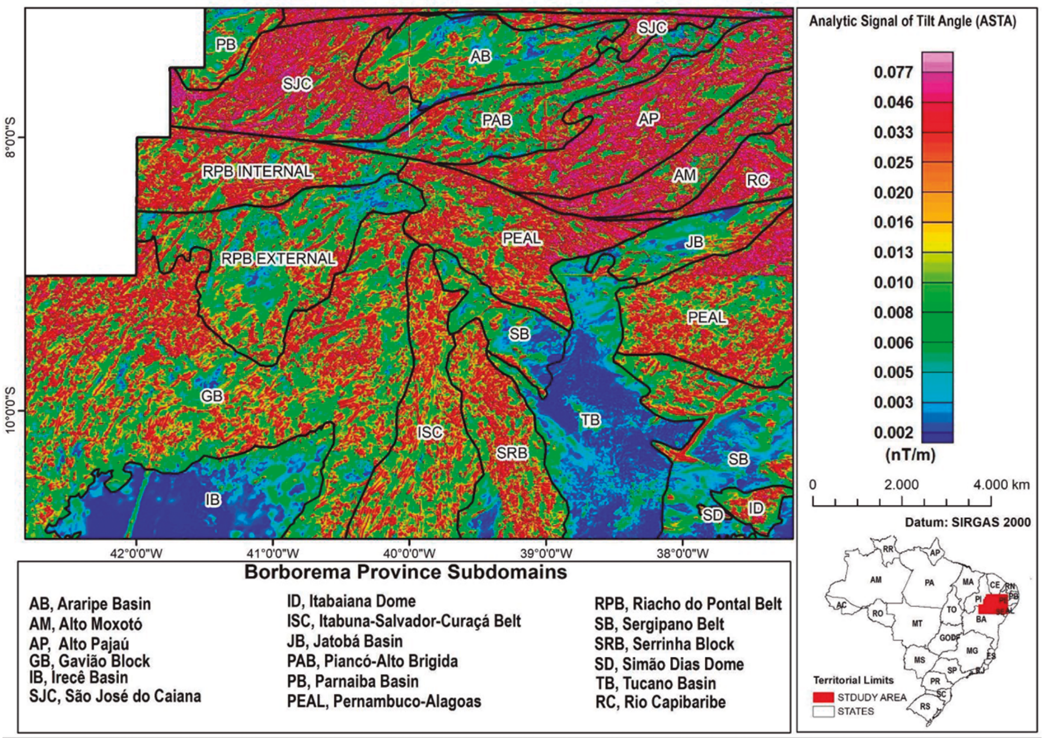

Figure 6. Border detection map by ASTA method with ascending continuation at 0.266 km.

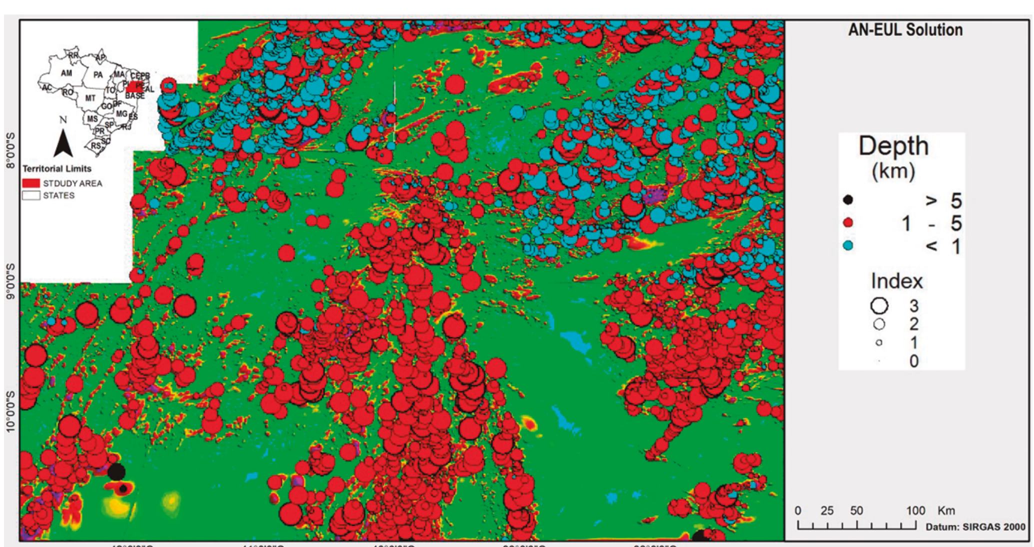

Figure 7. An-Euler solution.

The Bouguer anomaly image (Fig. 8) reveals gravity anomalies in the northern part of the craton ranging from -69.1 to -53.6 mGal, indicating a low-density contrast in this region, possibly associated with the Gavião Block. However, in the eastern region, a more marked density contrast is noticeable, ranging from -51.0 to -33.3 mGal, suggesting the possibility that these anomalies are associated with granitoids and dykes formed during Paleoproterozoic collisions and the amalgamation of Archean blocks. These elements include the Gavião, Jequié and Serrinha blocks, as well as the Itabuna-Salvador-Curaçá Belt (Barbosa et al., 2012a; de Menezes Leal et al., 2012).

Notably, the N-S orientation of the Itiúba granitoid, within the Itabuna-Salvador-Curaçá Belt, corresponds with the orientation observed in the vertical derivative (Dz), indicating a prominent N-S orientation in the SFC.

Towards the end of the Paleoproterozoic era, this paleocontinent underwent a series of rift events, forming sedimentary basins. These rifts contributed to the deposition of the Espinhaço Supergroup and, during the Neoproterozoic, the São Francisco Supergroup. However, subsequent tectonic events, such as folding and faulting at the end of the Neoproterozoic, during the Brasiliano orogeny, disrupted these rift systems (Cruz and Alkmim, 2006).

In the Bouguer anomaly map, gravity anomalies in the northern part of the SFC range from -102.6 to -73.6 mGal, indicating a lower-density contrast. This is attributed to the presence of Neoproterozoic cover rocks within this region, specifically the carbonate and siliciclastic rocks of the Bebedouro and Salitre formations, part of the Irecê Basin (Cruz and Alkmim, 2006; Guimaraes et al., 2011). These formations are well-defined along their edges (Fig. 6) and exhibit low magnetic susceptibility, contributing to the reduced magnetic signatures in this area.

Figure 8 provides a map of the Bouguer anomaly, offering significant insights into the gravimetric characteristics of the study area. Key observations from this map include high gravimetric signatures in the Transversal Borborema Province and peculiar gravimetric signatures in the Araripe Basin. The Transversal Borborema Province is predominantly characterized by high gravimetric signatures, ranging from -47.7 to -18.9 mGals. Interestingly, the Araripe Basin exhibits distinct gravimetric signatures characterized by lower values when compared to the surrounding regions.

The observations from this map include gravity anomalies in the Riacho do Pontal and Surrounding Domains. In the inner part of the Riacho do Pontal Belt, a gravity anomaly ranging from -36.6 to -18.9 mGal is observed. This anomaly extends into the Pernambuco-Alagoas Geotectonic Domain and the Sergipe Belt.

The SFC displays a significant gravity anomaly ranging from -73.6 to -102.6 mGal in the Irece Basin. A similar anomaly pattern is observed in the Tucano and Jatobá Basins, with consistent variations. In the SFC, the gravity anomaly ranges from -69.1 to -51.0 mGal, but it varies between -46.6 to -33.3 mGal in the eastern part of the craton.

These Bouguer anomaly data are instrumental for crustal modeling, aiding in the understanding of subsurface geological structures and variations in density within the study area.

Additionally, Figure 8 presents five geophysical profiles oriented in the NW-SE direction, perpendicular to the orientations of magnetic lineaments observed in the DZ. These profiles were utilized for geological and geophysical modeling, contributing to a more comprehensive understanding of the subsurface features and characteristics.

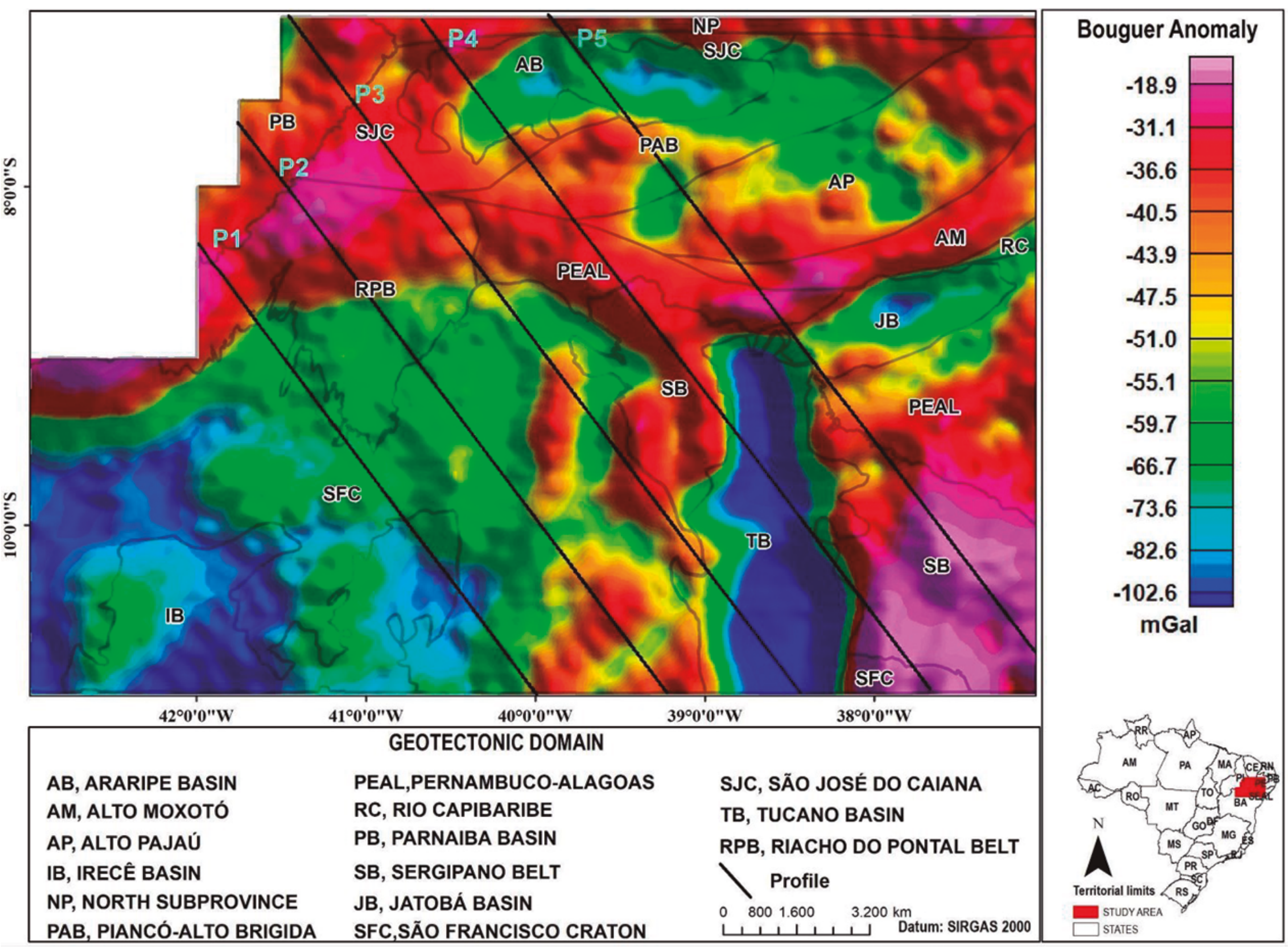

Figure 8. Bouguer anomaly image.

Figure 9 presents the Moho thickness map, which reveals significant variations in Moho depth across the study area, ranging from 36 to 43.8 kilometers. This map provides valuable insights into the region's structural characteristics of the Earth's crust.

One of the key observations from this map is the variability in Moho depth, indicating diverse geological features and tectonic processes at play. The depth of the Moho, marking the boundary between the Earth's crust and mantle, is an essential parameter for understanding the subsurface geology. Examining different geological domains within the study area, we find distinct Moho depths. The SFC exhibits a relatively deep Moho at approximately 41.6 kilometers, indicative of a thicker crust in this ancient geological formation. In contrast, the Irecê Basin shows a shallower Moho depth of around 39.4 kilometers, suggesting a thinner crust in this basin. Within the Riacho do Pontal Belt, the Moho depth is observed at 38.2 kilometers, highlighting variations in crustal thickness within this geological unit. The Pernambuco-Alagoas and Sergipano Belt display similar Moho depths, approximately 38.2 kilometers and 37.4 kilometers, respectively, indicating consistent crustal characteristics in these belts.

These findings underscore the geological complexity of the study area, with significant variations in Moho depth across different geological settings. Understanding these variations is crucial for interpreting the region's tectonic processes, seismicity, and geological evolution. Notably, these major geological domains within the study area, such as the SFC, Irecê Basin, Riacho do Pontal Belt, Pernambuco-Alagoas Belt, and Sergipano Belt, are characterized by relatively deeper Moho depths compared to other domains within the Transversal Borborema region.

Indeed, the Moho depth values obtained from this study serve as crucial a priori information for the subsequent modeling of the Earth's crust within the study area. These values provide essential insights into the subsurface geological structure and the significant variations in Moho depth across various geological domains. Such information is fundamental for advancing our understanding of the complex geological and geophysical characteristics of the region, ultimately aiding in more accurate and comprehensive geological modeling and interpretation.

Figure 10 presents the crustal model for Profile 1. This model comprises nine distinct geotectonic domains, which have been identified and designated as follows: Parnaíba Basin and Block (1), Riacho do Pontal Belt (2), Intrusion (2.1), São Francisco Craton (3), Irecê Basin (4), in addition to Upper Crustal Layers (16), Lower Crust (17), and Lithospheric Mantle (18). The density values used in the modeling are provided in Table 1A (Appendix A). The results reveal that the depths of these domains exhibit distinct values, as follows: (1) ranges from 0 to 3.2 kilometers, (2) varies between 8.0 and 13.0 kilometers, (2.1) has a depth of 7.0 kilometers, (3) ranges from 5.0 to 18.0 kilometers, with an average Moho thickness ranging from 41.0 to 42.0 kilometers.

The variation of the calculated parameters stabilizes in line with the observed parameters, indicating a good fit for the model. It showed a satisfactory representation of the dimensions of the bodies in the subsurface. There is a convergence between the solid and dashed curves, especially in the transition region between the Borborema province and the SFC and in the configuration of the Irece Basin. This suggests that the model resembles the relief of the basement.

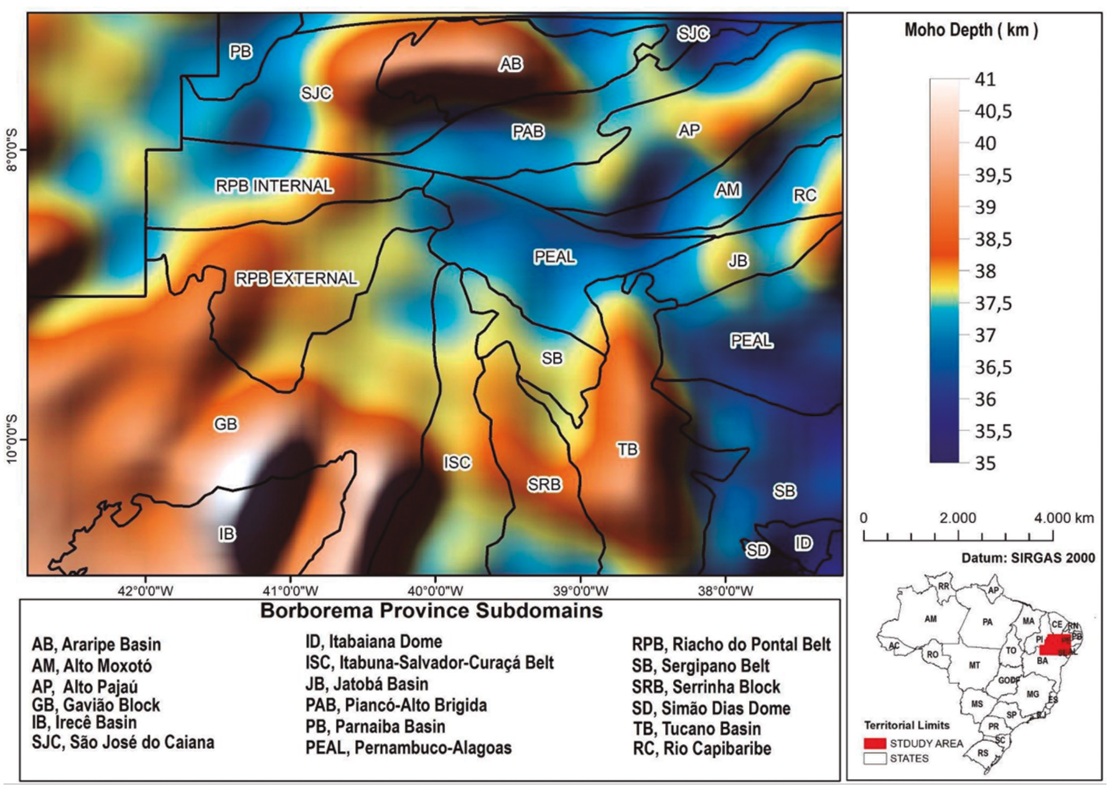

Figure 9. Moho depth, referring to the studied area.

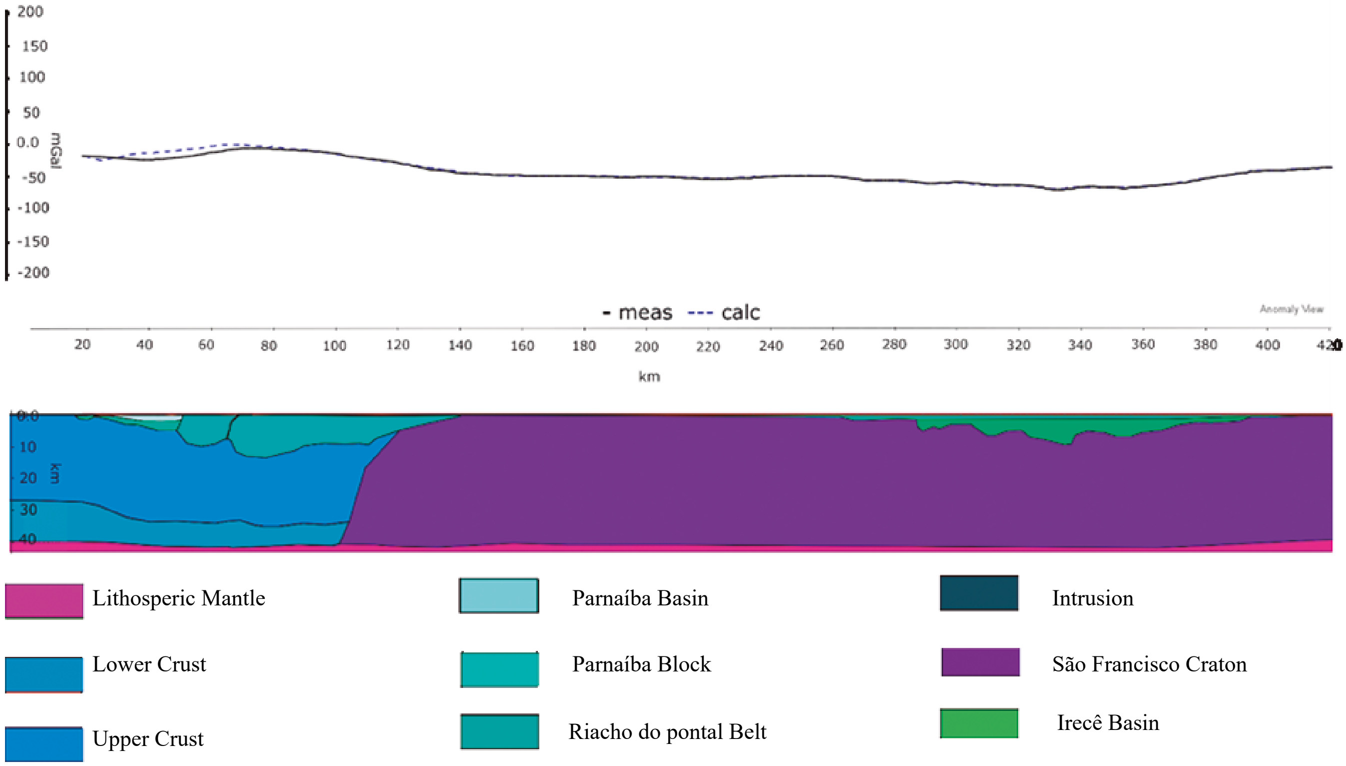

Figure 10. The model of the profile P1, represent the domains.

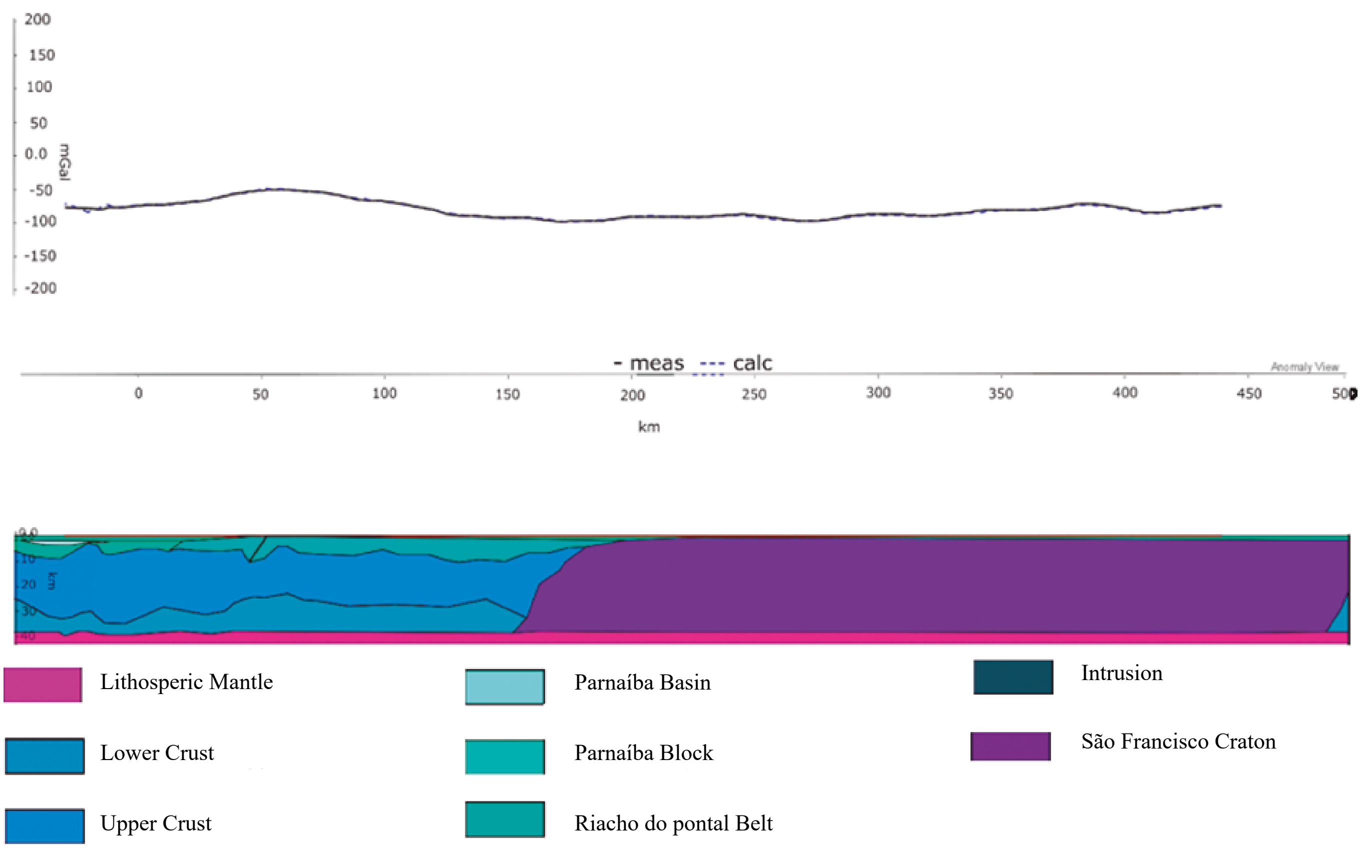

Figure 11. The model of the profile P2 shows the geotectonic domains.

Figure 11 displays the corresponding crustal model for Profile 2, with a horizontal extent of 500 kilometers. This model consists of seven distinct geotectonic domains, designated as follows: Parnaíba Basin and Block (1), Riacho do Pontal Belt (2), Intrusion (2.1), São Francisco Craton (3), along with Upper Crustal Layers (16), Lower Crust (17), and Lithospheric Mantle (18).

Our findings reveal significant variations in the depths of each domain, as follows: (1) ranges from 0 to 3.0 kilometers, similar to the depth observed in the previous profile, (2) falls within the range of 5.0 to 11.0 kilometers, (2.1) has a depth of 10.0 kilometers, (3) encompasses depths between 6.0 and 14.0 kilometers, with a Moho depth varying from 36.0 to 39.5 kilometers.

The result is achieved when the variation of the calculated parameters stabilizes in line with the observed parameters. The model showed a satisfactory representation of the dimensions of the bodies in the subsurface. The solid curves represent the isolines of the observed data, while the dashed curves represent the anomalies calculated for the model. These curves converge at the contact between the Borborema province and the SFC. With the parameters used to build the model, the observed anomalous field is equivalent to the field generated by the model.

Figure 12 presents an additional model for Profile 3, highlighting distinct geotectonic domains, specifically: Parnaíba Basin and Block (1), Riacho do Pontal Belt (2), São Francisco Craton (3), Tucano Basin (5), São José do Caiana (6), along with Upper Crustal Layers (16), Lower Crust (17), and Lithospheric Mantle (18).

For this profile, significant variability in the depths of these domains was observed, as described below: Domains (1): Depths ranging up to 4.0 kilometers; (2): Depths varying between 4.0 and 8.0 kilometers; (3): Depths ranging from 4.0 to 25.0 kilometers; (5): Displaying depths from 3.0 to 8.0 kilometers; (6): Depths oscillating between 4.0 and 10.0 kilometers. The Moho depths within these domains range from 37.0 to 41.0 kilometers.

The model generated correlates well with the observed data, as illustrated in Figure 12. The curves of the observed data and the calculated data show a satisfactory correlation with the generated model. The gravimetric model reveals a decrease in the intensity of the gravimetric field, which can be interpreted as due to thick sediment sequences and a symmetrical distribution of densities, suggesting uniformity of composition both laterally and at depth in the direction of the craton. When examining the plan representation of the density distribution model (Fig. 12), a radial distribution of densities can be seen both in the Borborema province and in the craton portion, with an adequate fit between the solid and dashed curves.

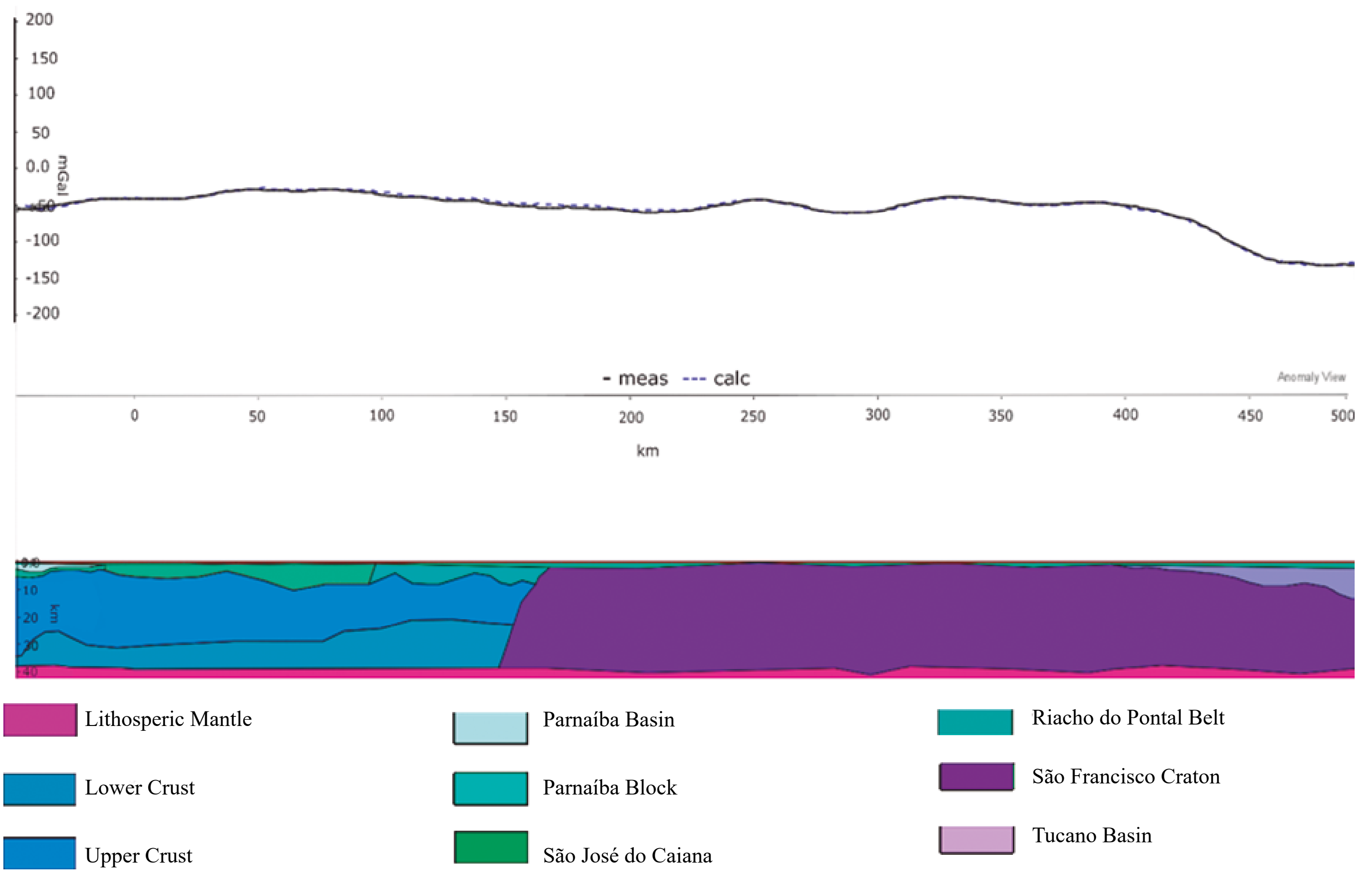

Figure 12. The model of profile P3 exposes the geotectonic domains.

Figure 13 displays the model for Profile 4, consisting of various geotectonic domains, namely: Tucano Basin and Block (5), São José do Caiana (6), Northern Subprovince (6), Araripe Basin and Block (7), Piancó-Alto Brígida (9), Pernambuco-Alagoas (10), Sergipano Belt (11), Dense Crust (12), along with Upper Crustal Layers (16), Lower Crust (17), and Lithospheric Mantle (18).

In this profile, the depths of these geological domains exhibit the following ranges: Domains (5): Depths not exceeding 3.0 kilometers; (6): Depths varying from 7.0 to 10.0 kilometers; (7): Also varying from 7.0 to 10.0 kilometers; (9): Depth variations ranging from 2.0 to 8.0 kilometers; (10): Depths situated between 2.0 and 9.0 kilometers; (11): Extending within the range of 6 to 11 kilometers. Furthermore, the Moho depths in this profile range from 37.0 to 41.0 kilometers, corresponding to the Moho thickness.

The model generated is in line with the model in Figure 12, showing a good correlation with the observed data, as illustrated in Figure 13. The curves of the observed and calculated data show a satisfactory correlation with the model generated. The gravimetric model reveals a varied distribution of densities, indicating compositional variation both laterally and in depth in the direction of the Sergipano Belt.

Figure 14 presents the model for Profile 5, comprising various geotectonic domains, namely: Northern Subprovince (7), Araripe Basin (8), Piancó-Alto Brígida (9), Pernambuco-Alagoas (10), Sergipano Belt (11), Jatobá Basin (15), Alto Pajeú (13), Alto Moxotó (14), along with Upper Crustal Layers (16), Lower Crust (17), and Lithospheric Mantle (18).

It can be observed that the depths of these domains exhibit the following variations: Domain (7): Depths ranging from 5.0 to 6.0 kilometers; (8): Depths varying between 1.5 and 2.7 kilometers; (9): Depth variations ranging from 2.0 to 7.0 kilometers; (10): Depths ranging from 4.0 to 7.0 kilometers; (11): Depths between 5.0 and 15.0 kilometers; (15): Depths from 2.0 to 4.0 kilometers; (13): Depths ranging from 10.0 to 15.0 kilometers. (14): Depths between 4.0 and 6.0 kilometers.

The model generated correlates satisfactorily with the observed data, as shown in Figure 13. Throughout the profile, the gravimetric anomaly shows significant homogeneity, characterized by a decrease in the intensity of the gravimetric field mainly in the NW-SE direction. This decrease in intensity can be attributed to the presence of thick sediment sequences. When analyzing the plan representation of the density distribution model (Figure 13), there is a variation in the distribution of densities in the Borborema province and in the portion of the Sergipano Belt.

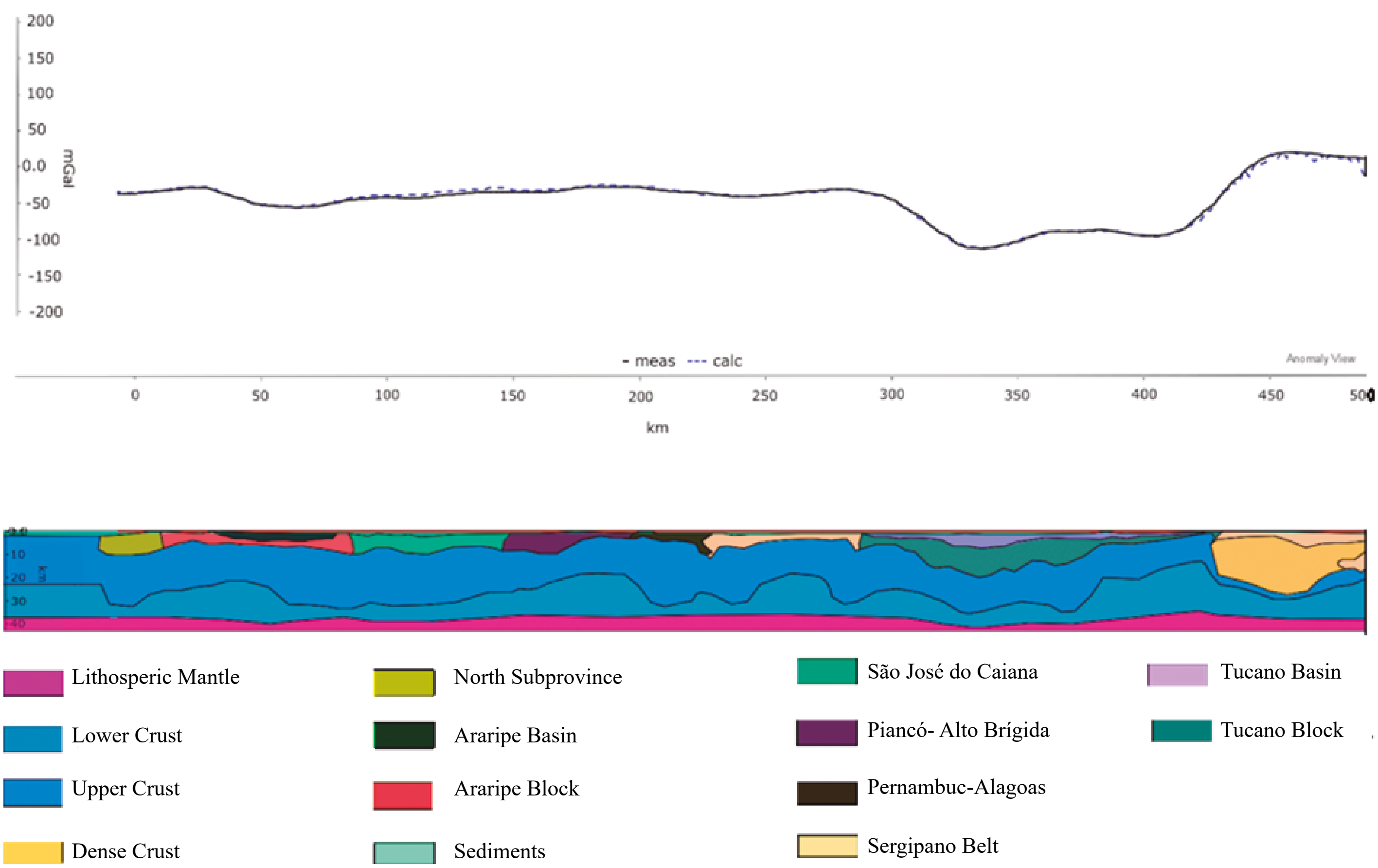

Figure 13. The model of the profile P4 presents the geotectonic domains.

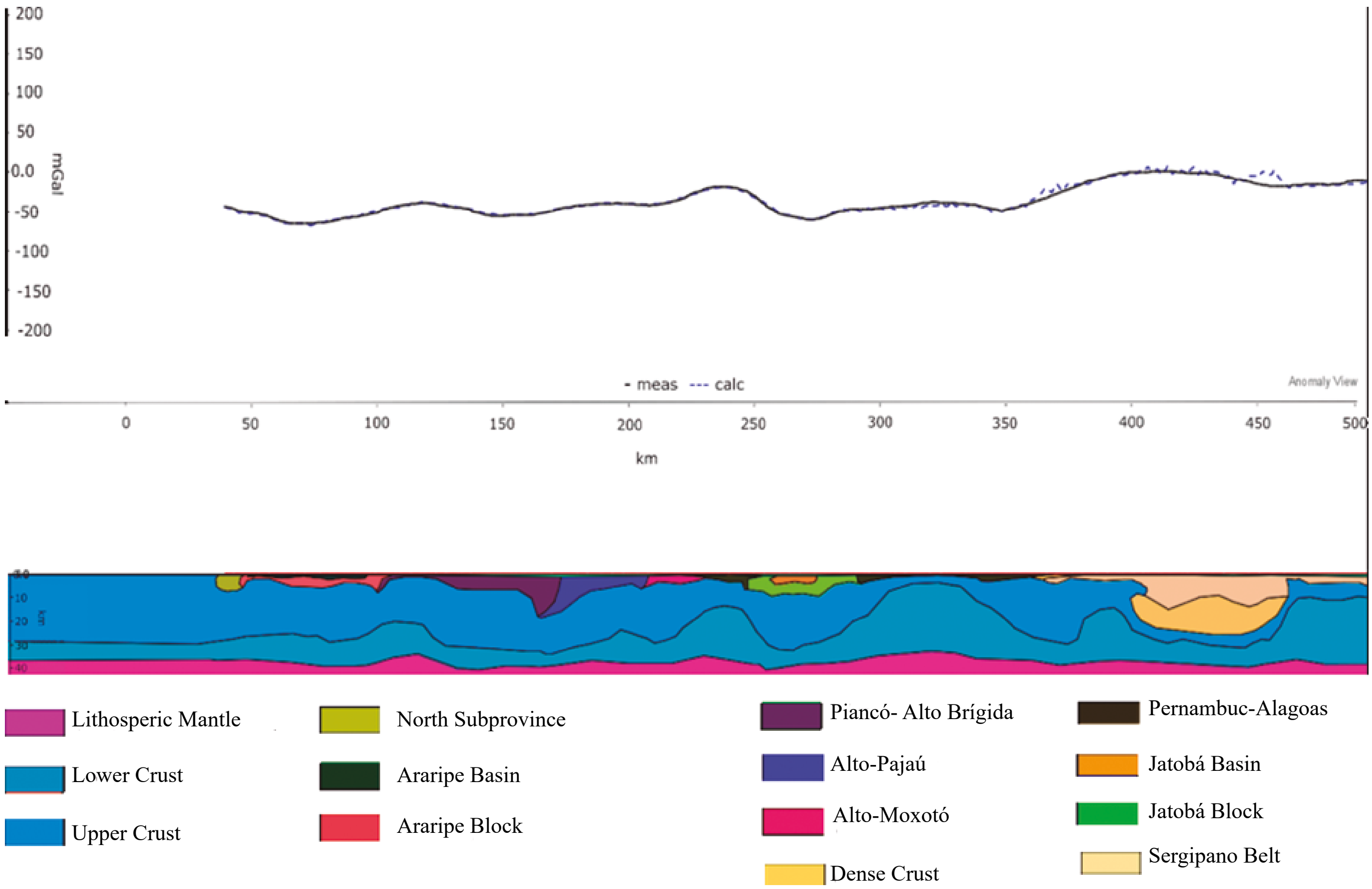

Figure 14. The model of the profile P5 presents the geotectonic domains.

Furthermore, the depths within these domains range from 39.0 to 41.0 kilometers, corresponding to the crustal thickness. In simplified form, table 01 shows the average values obtained in the modeling. Figure 15 displays the compilation of all the crustal models in the five profiles, generating a three-dimensional model.

Table 1. Values obtained in modeling

Acronym	**Domain**	**Upper Crust** *(km)*	**Middle Crust** *(km)*	**Moho** *(km)*	**Upper Crust Density** *(kg/m³)*
SFC	São Francisco Craton	16.2	26.2	41.6	2700
IB	Irecê Basin	7.2	27.0	39.4	2550
RPB	Riacho do Pontal Belt	12.5	25.3	38.2	2660
PEAL	Pernambuco-Alagoas	7.5	23.3	38.2	2700
SB	Sergipano Belt	14.3	24.2	37.4	2560
JB	Jatobá Basin	4.3	24.8	39.5	2550
TB	Tucano Basin	7.2	30.1	38.4	2550
PB	Parnaíba Basin	3.7	25.7	39.4	2550
SJC	São José Caiana	10.3	28.9	38.4	2740

(Continued)

Acronym	**Domain**	**Upper Crust** *(km)*	**Middle Crust** *(km)*	**Moho** *(km)*	**Upper Crust Density** *(kg/m³)*
SFC	São Francisco Craton	16.2	26.2	41.6	2700
IB	Irecê Basin	7.2	27.0	39.4	2550
RPB	Riacho do Pontal Belt	12.5	25.3	38.2	2660
PEAL	Pernambuco-Alagoas	7.5	23.3	38.2	2700
SB	Sergipano Belt	14.3	24.2	37.4	2560
JB	Jatobá Basin	4.3	24.8	39.5	2550
TB	Tucano Basin	7.2	30.1	38.4	2550
PB	Parnaíba Basin	3.7	25.7	39.4	2550
AB	Araripe Basin	2.7	21.6	39.5	2550
PB	Piancó-Alto Brígida	10.0	24.6	36.8	2680
AP	Alto-Pajeú	14.1	23.9	37.8	2665
AM	Alto-Moxotó	11.2	22.9	37.2	2690

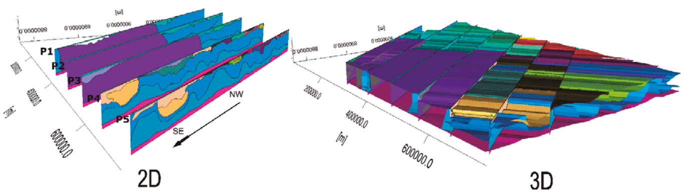

Figure 15. Crustal model 2D and 3D of the density distribution in the subsurface of the respective profiles in Figure 8.

5. Discussion

The SFC is primarily composed of Archean terrains. During the late Paleoproterozoic era, collisions resulted in the amalgamation of Archean rock units within the craton, including the Gavião Block and Jequié Complex (Barbosa and Barbosa, 2017). Archean and Paleoproterozoic rocks form the basement of Bahia state. In the northern part of the craton, the Gavião Block is predominant, characterized by metamorphic terrains consisting of gneisses, migmatites, and orthogneisses dating back 3.6 Ga. East of the Gavião Block lies the Itabuna-Salvador-Curaçá Belt, comprising granulites such as tonalites, enderbitic rocks, charnockites, and leucogabbros. Further east, the Serrinha Block is composed of metamorphic rocks like gneisses and migmatites with amphibolite, quartzites, while the Uauá Block consists of gneiss, orthogneiss, and orthogranodiorite (Barbosa et al., 2012b; Cruz and Alkmim, 2017).

The Moho thickness beneath the SFC, approximately 41.6 km, aligns with the findings of Feng et al. (2007) and Assumpção and Lopes (2013), providing a robust confirmation. Our modeling revealed the depth of the Irecê Basin to be 8 km, in line with the findings of D´Angelo et al. (2019). The Brasiliano orogeny, a key focus of our study, intensified collision events along the boundaries between the paleocontinent and the Borborema Province, leading to foldings, deformations, and high-grade metamorphism. This process gave rise to fold belts in Sergipe, Riacho do Pontal, and Rio Preto (Barbosa and Sabaté, 2004). The northernmost internal part of the Riacho do Pontal Belt encompasses the Paulistana, Santa Filomena, and Morro Branco complexes, which are intruded by magmatic bodies such as syn-collisional granites (Aldeia and Rajada Suites) and alkaline granites formed after the collision (Serra da Aldeia Suite). In contrast, the southernmost portion comprises metasedimentary units ranging from metapelites to metagraywacke (Caxito, 2013; Caxito et al., 2014, 2020).

The delineation of the Riacho do Pontal Belt is evident in Figure 5, illustrating its connection with the SFC to the north and its extension eastward towards Pernambuco-Alagoas. The Bouguer anomaly map highlights anomalies in its northern portion ranging from -33.3 to -18.9 mGal (Figure 8) and total magnetic field variations between 47.66 and 97.11 nT (Figure 4). Conversely, the southern part displays lower Bouguer anomalies, indicating reduced magnetic susceptibility. This sharp contrast in density and magnetic susceptibility is attributed to the presence of magmatic bodies resulting from collisional events and the Neoproterozoic low-density contrast associated with metasedimentary rocks of the Casa Nova group.

The Pernambuco-Alagoas domain encompasses a variety of high-grade Archean, Paleoproterozoic, metavolcanic-sedimentary rocks, and granitic terrains (Neves and da Silva Filho, 2019; Lima, 2018). The presence of magnetic intrusions, such as granitic bodies, indicates significant density contrasts associated with the Brasiliano orogeny. These igneous intrusions were identified using magnetometric and airborne gamma-spectrometric data, revealing an NE-SW oriented transcurrent shear zone (Lima et al., 2021). Similarly, the Sergipano Belt experienced multiple episodes of regional metamorphism and tectonic deformation during the orogenic event. The magnetic results highlight low susceptibility in the southern part of the Sergipe Belt (Figure 5), likely due to metasedimentary rocks, as noted by Allard and Hurst (1969). In the transverse section of the Borborema Province, several domains are observed, including São José do Caiana, Piancó-Alto Brígida, Alto Pajeú, Alto Moxotó, Rio Capibaribe, and Phanerozoic cover sequences in the Araripe basin. These domains are delineated by two major shear zones: the Pernambuco and Patos shear zones (Santos and Medeiros, 1999; Medeiros, 2004).

This region comprises Paleoproterozoic gneisses dating back to 2.0 and 2.2 Ga, metavolcanic and metasedimentary rocks aged around 995 and 960 Ma due to the Cariris Velhos event, and various plutonic intrusions associated with the Brasiliano orogenic event. Plutonic intrusions have been identified and interpreted by various researchers (Schmus et al., 2011; Sialand and Ferreira, 2016; Neves et al., 2016; Caxito et al., 2021). Concerning magnetic structures, two significant shear zones, Pernambuco and Patos, are evident, along with possible NE-NW oriented lineaments associated with the disruption of West Gondwana (Figure 4). The results of Moho depth analysis indicate that the Transversal Borborema Province has a thinner crust, approximately 38.5 km, compared to the SFC with a thickness of 41.6 km (Figure 7). These findings are in line with observations made in Fianco (2019), where the collisional suture zone between the Borborema Province and the SFC is characterized by a positive and negative peak in the Bouguer anomaly profile, indicating the collision and subsequent stretching along this boundary.

In summary, this study offers valuable insights into the geological history and subsurface structure of the SFC and surrounding regions, providing a better understanding of the complex tectonic events that have shaped the area over billions of years. The integration of magnetic and gravity data, along with geological and geophysical models, has facilitated a more comprehensive understanding of the region's geological evolution and structural characteristics, as depicted in figure 16.

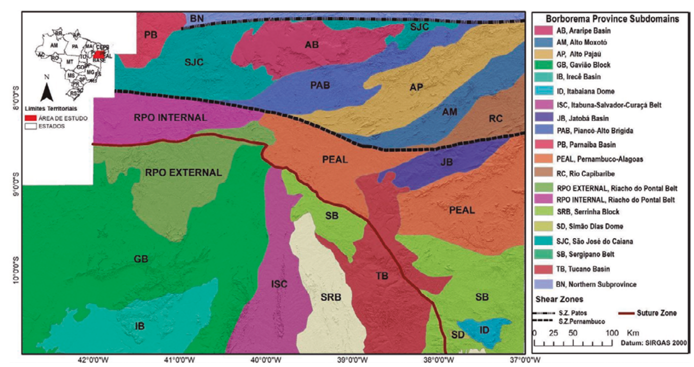

Figure 16. Geological Map New with Geophysical Interpretation.

6. Conclusions

In this research, we utilized gravity, magnetic, geoid anomaly and topographic data to provide a better understanding of the crustal structure in the western Borborema Province. Our main objectives were to delineate crustal block boundaries, ascertain the orientations of regional lineaments, establish top depths of magnetic sources, estimate Moho thickness, and construct crustal models through the integration of geological and geophysical data. Our results, when correlated with lithological data from diverse geological domains within the study area, facilitated the precise delineation of the suture zone between these blocks. Magnetic anomalies were predominantly low in the outer part of the Riacho do Pontal Belt (RPO) and the southeastern Sergipano Belt but exhibited high values in the upper regions of the province. Additionally, Moho thickness in these areas was observed to be relatively modest.

Furthermore, we identified a range of magnetic signatures and gravity anomalies across the study region, characterized by both positive and negative deviations. The use of filtering techniques enabled us to pinpoint contacts between distinct tectonic domains, such as the SFC and the Riacho do Pontal Belt. These findings, when combined with geological domain maps, allowed for accurate determination of depth-related information for various geological features.

Figure 5 depicts the tectonic framework of the area, characterized by geophysical lineaments primarily oriented in a northeast-southwest direction. This alignment corresponds to the predominant direction of emergent features associated with the Brasiliano extensional orogenic event.

Regarding the Moho, our findings confirm a crustal thickness of approximately 41.6 km for the SFC. In the northern part, the SFC basement shows continuity, especially in the external domain of the Riacho do Pontal Belt.

Qualitative analysis of the results revealed distinct signatures for supracrustal and basement rocks. The crustal thinning observed in profiles 2 and 3 can be attributed to the collision between the SFC and the Borborema

Province. The Pernambuco-Alagoas domain, exhibiting high-intensity magnetic relief, corresponds to regions with high magnetic susceptibility in our modeling. Conversely, the southeastern part of the Sergipano Belt exhibits a low magnetic anomaly, possibly due to lower susceptibility zones within the belt, unlike the northeastern region. This suggests that the observed crustal thinning may be associated with the separation of the South American and African plates.

High magnetic signatures observed within the internal regions of the Riacho do Pontal Belt, Pernambuco-Alagoas, Sergipano Belt, and the eastern part of the Transverse Borborema Province suggest that suture zones between the South American and African plates likely formed in a southeast-northwest direction. Additionally, the contours observed in the western section of the vertical derivative map (Dz), oriented northeast-southwest, appear perpendicular to the direction of collisional forces between the plates. The identified suture zone, characterized by high magnetic signatures and Moho depth, can be interpreted as an intensified expression of the tectonic boundary separating the Borborema Province and the SFC. This collisional boundary is presumed to extend further south based on the evidence presented.

These conclusions offer a comprehensive understanding of the geological, tectonic, and geophysical structure of the studied region, highlighting the complex geodynamic processes that have shaped it over geological time.

Acknowledgments

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APPENDIX A. Density values employed in gravity modeling

The physical parameters employed in the crustal modeling process are detailed in Table 1A below.

Table 1A- Density values assigned in 3-D gravity modeling.

Domain	**Density** *(kg/m³)*
Sediments	2550
São Francisco Craton	2700
Irecê Basin	2550
Riacho do Pontal belt	2660
Pernambuco-Alagoas	2700
Sergipano Belt	2560
Jatobá Basin	2550
Jatobá block	2600
Tucano Basin	2550
Tucano block	2680
Parnaíba Basin	2550
Parnaíba block	2690
São José do Caiana	2740
Araripe Basin	2550
Piancó-Alto-Brígida	2680
AltoPajeú	2650
Alto Moxotó	2690
North Subprovince	2680
Intrusion	3900
Upper Crust	2790
Lower Crust	2950
Moho	3330
Dense Crust	3100

Source: The authors (2024).