REVISTA DE GEOCIÊNCIAS DO NORDESTE

Northeast Geosciences Journal

ISSN: 2447-3359

v. 8, nº 1 (2022)

https://doi.org/10.21680/2447-3359.2022v8n1ID21766

Characterization of the Basement Adjacent to the Sergipe Sub-Basin, Brazil: Direct and inverse two-dimensional modeling of gravity data

Caracterização do Embasamento Adjacente à Sub-Bacia Sergipe, Brasil: Modelagem Bidimensional direta e inversa de dados gravimétricos

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Abstract: In this work, the subsurface structure of the basement adjacent to the Sergipe sub-basin was characterized using gravity data in order to provide information about the density contrast distribution, geometry, and depths of the main sources through the acquisition, processing, and direct and inverse two-dimensional modeling of these data. Such information generated an optimization of the understanding in relation to the basement framework and its relationship with the sedimentary section of the Sergipe sub-basin. The study was based on geological information, density of rocks collected in the locality, gravity data, and interpretation of magnetic maps. The two-dimensional gravity inversion allowed us to reach an optimized result for the density contrast value of the main sources, which was 0.15-0.20 g/cm³. Anomalous sources were mapped reaching depths of 5 to 7 km. In the sedimentary region of the sub-basin, its sediment-basement interface reaches a limit of 4 to 5 km in depth. The integration of these data allowed for a more realistic subsurface density model, as well as an interpretive geological model, and predicts that the dome regions of this basement are accommodated in the upper part of the crust.

Keywords: Gravity modeling; Sergipe-Alagoas basin; Gravity inversion.

Resumo: Neste trabalho, a estrutura em subsuperfície do embasamento adjacente à sub-bacia Sergipe foi caracterizada utilizando dados gravimétricos que forneceram informações sobre a distribuição do contraste de densidade, a geometria e profundidades das principais fontes, a partir da aquisição, processamento, e modelagem bidimensional direta e inversa desses dados. Tais informações geraram uma otimização do entendimento em relação ao arcabouço do embasamento e sua relação com a seção sedimentar da sub-bacia Sergipe. Tivemos como base do estudo informações geológicas, densidade das rochas coletadas na localidade, dados gravimétricos, e interpretação de mapas magnéticos. A inversão bidimensional gravimétrica nos permitiu chegar a um resultado otimizado para o valor do contraste de densidade das principais fontes que foi de 0,15-0,20 g/cm³. Algumas fontes anômalas foram mapeadas alcançando profundidades de 5 a 7 km. Na região sedimentar da sub-bacia, a sua interface sedimento-embasamento chega ao limite de 4 a 5 km de profundidade. A integração desses dados permitiu ter um modelo de densidade em subsuperfície mais realista, assim como um modelo geológico interpretativo, e prevê que as regiões dômicas desse embasamento estão acomodados na parte superior da crosta.

Palavras-Chave: Modelagem gravimétrica; Bacia Sergipe-Alagoas; Inversão gravimétrica.

Recebido: 17/07/2020 Aceito: 31/08/2021; Publicado: 27/01/2022.

1. Introduction

In this paper, direct and inverse two-dimensional modeling of gravity data was performed in the region of the Sergipe sub-basin in order to obtain information on density contrast, lateral contacts, geometry, and depth of sources located in the subsurface of the basement adjacent to the sub-basin.

The description of the geological context in the study area has been well explained (SANTOS *et al.*, 2000; RANCAN *et al.*, 2008; MENDES *et al.*, 2017), however the subsurface models are scarce. Thus, geophysics is employed as an effective tool for producing models of the distribution of subsurface physical properties in the region.

The use of the gravity method offered the possibility to study the environment at regional scales, with low cost and a good amount of quality data available, through the detection of anomalies related to the variation of density contrasts in the subsurface. Despite their advantages, the potential methods present the problem of ambiguity in their interpretation, which was solved with the introduction of geological information, physical properties of the rocks from surface samples and magnetic data for further correlation with the gravity data. Such information was important to support the geological interpretations of the region, and could indicate fault reactivation, basement uplift, or crustal thickening, besides providing essential information to produce subsurface models.

The inverse modeling included geological and geophysical information from previous works in the area, such as Dutra *et al.* (2019), Dutra *et al.* (2017) and Argollo *et al.* (2011), bringing respectively themes about the integration of results regarding the tectonic control of the southern part of the Sergipan Belt, determination of thickness of the sediment-basement interface of the Sergipe sub-basin and the production of radiogenic heat in the domains studied here.

Despite its advanced exploratory status, the Sergipe sedimentary sub-basin presents areas with unexplored potential that deserve attention. One of the ways to study these possible mineral exploration sites is to obtain characteristics of the basement adjacent to it, assuming that the base of its sediments, at least petrophysically, is similar to the studied area. Thus, it is possible to extrapolate the characteristics and structures recognized in the neighboring portion to the basement of the basin.

2. Geological settings

The Sergipe-Alagoas Basin, located in the northeast of the Brazilian continental margin, with a total area of about 44,370 km² (onshore and offshore) and a general orientation NNE-SSW, is located between parallels 9°S and 11°30'S and meridians 34°30'W and 37°30'W. It is limited to the north by the Pernambuco-Paraíba Basin through the upper Maragogi and to the south by the Jacuípe Basin. The Sergipe-Alagoas Basin has an internal boundary, marked by the Japoatã Penedo High, which subdivides it into two important sedimentary complexes, sub-basin Sergipe to the South (SBSE) and Alagoas to the North (SBAL) (ANP, 2017).

The origin of the Sergipe-Alagoas Basin relatedness to the separation of the South American and African plates from the fracturing and rupture of the mega continent Gondwana, propagated from south to north, although there are sedimentary records prior to this event (ANP, 2017). Recently, in 2019, a news release by Gas Energy (VICTAL, 2019) announced the discovery of six new natural gas fields in the Sergipe-Alagoas region by Petrobras, increasing interest in research in the region. Besides being important for the study of the basin, the basement in question can be treated as a latent environment for deeper research about the chronological geotectonics of the geotectonic domains covered or further search for possible exploration points of mineral interest bodies (MENDES *et al.*, 2009).

The adjacent basement of the Sergipe sub-basin is inserted in the Borborema Meridional sub-province and in part of the São Francisco Craton. In its extension there are subdivisions (Figure 1), known as geotectonic domains, that constitute this basement, such as: the Salvador-Esplanada-Boquim (SEB) domain related to the São Francisco Craton (CSF); Estância, Canudos-Vaza-Barris, Canindé, Macururé domains that are related to the Sergipan Belt (FS); Rio Coruripe and Pernambuco-Alagoas domains (SANTOS *et al.*, 2000). Each domain is geologically divided according to structural and stratigraphic aspects that are characteristic of the area and different from each other.

Besides the structural elements of the highlighted domains, there are two dome units inserted in the basement, which are lithologically different from their surroundings and show important signatures in geophysical measurements. Such structures are the Itabaiana and Girau do Ponciano domes. The first one outcrops in the Canudo-Vaza-Barris domain and is located between two important shear zones, São Miguel de Aleixo and Itabaiana. The second, Domo Girau do Ponciano, is situated in the Macururé Domain, adjacent to the Belo Monte Jeremoabo shear zone. Our main interest in this work is to study the basement adjacent to the Sergipe sub-basin and its structures that provide significant information for the understanding of the crustal framework and the tectonic correlation between the São Francisco Craton and the southern part of the Sergipan Belt.

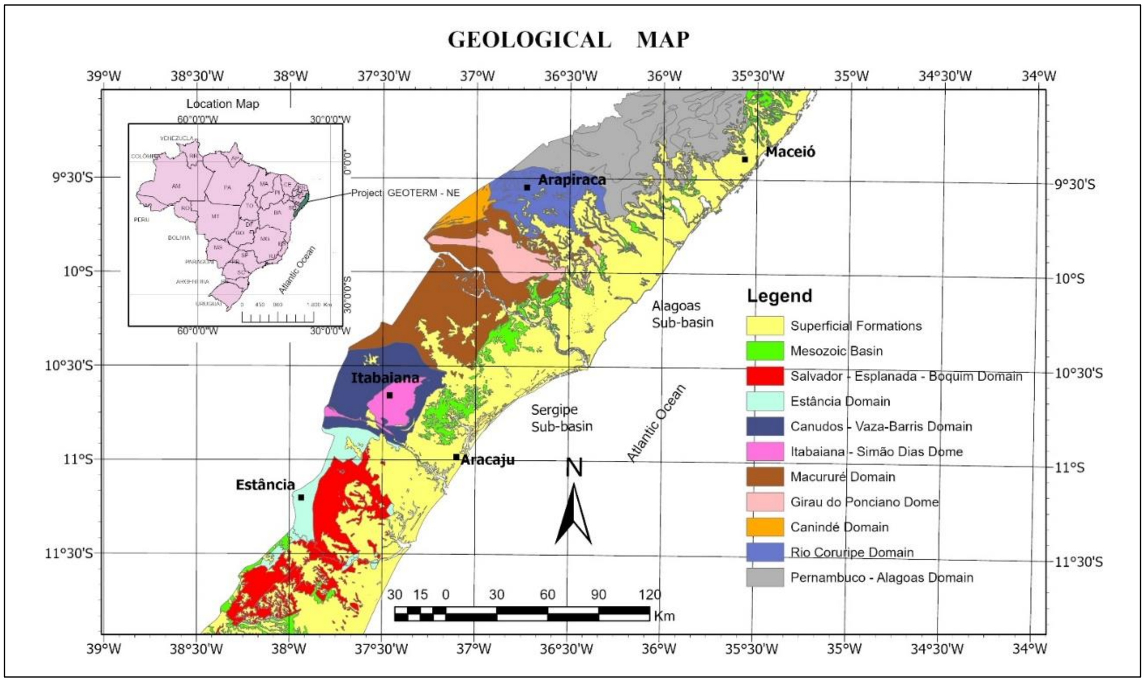

Figure 1 - Simplified geological map of the study region, containing indications of the geotectonic domains present. Source: Adapted from Argollo et al. (2011).

3. Data and methodology applied

The gravity data used in the direct and inverse modeling come from terrestrial surveys of the Geoterm project (IF-UFBA), in which measurements were made with a Scintrex CG-5 gravity meter, in addition to a planialtimetric survey with differential GPS. Data provided by the National Gravity Network through the ANP (Petrobras and other oil companies) and CPRM databases, and data supplied by the Brazilian Institute of Geography and Statistics (IBGE) completed the gravity information used in the research. In data processing, the step following acquisition, the necessary gravity reductions and appropriate treatments were performed to highlight the geological structures of interest in the surrounding basement, and thus generate maps and profiles for 2-D modeling. To obtain a more adequate interpretation of the spatial data and to plot the profiles for the modeling in convenient directions, we used magnetic data from the region.

Thus, we obtained the residual gravity anomaly curves required for the inversion process. This inversion modeling was based on a linear design, in which the substratum is represented by a homogeneous mesh of known position and size, but with unknown density contrast. The process consists of determining the density contrast in each cell and thereby delineating the geometry of the true source (GUILLEN *et al.*, 1984; LAST *et al.*, 1983; SILVA *et al.*, 2006). The density information was taken from rock samples made available by the Geoterm-UFBA Project (BOEKER, 2011). Acquiring information of depth, density contrast and/or geometry of bodies from the inversion, direct subsurface models were made, in which, the theoretical formulation of the two-dimensional modeling used allows the representation of lithological structures by polygons (TALWANI *et al.*, 1959).

3.1 Gravity Method

The gravity method is based on mapping the variation of gravity acceleration values that correspond to a lateral variation of density (ρ) in the subsurface, detecting anomalies derived from the contrast of the property in question. The higher the density of the body, the greater will be the gravitational attraction at that point, so in the case of a sedimentary basin, its depocenter should present low gravity values, given that its rocks generally have lower densities than its basement and the rocks in its surroundings, generating negative contrasts at the site.

Despite being a solid geophysical method with quality data available, it presents ambiguity problems, allowing several interpretations for the same anomaly curve analyzed. Therefore, to reduce errors in its conclusions, its examination should always be associated with other methods and information in a priory. Gravity acquisition is done with a gravimeter and can be done both from the air and from the ground.

Due to the irregular shape of the planet and its movements, we know that the value of gravitational acceleration (g) is not constant over the entire surface. Thus, to achieve our goal, the anomalies generated by the density variation in the subsurface, it is necessary to eliminate the other influences, thus performing the gravity reductions. For the gravity data used in this paper, the temporal and tidal, latitude, free-air and Bouguer corrections were performed, in addition to the drift correction intrinsic to the equipment used.

The Bouguer anomaly depends on the dimensions, density contrast and depth of the source. In this way, by observing the anomaly curves, it is possible to infer whether the body it belongs is shallower or deeper. Deep structures tend to produce flatter anomalies that occupy a larger area, while shallower structures tend to produce narrower anomalies with more defined amplitude.

During the processing step, in order to separate the anomaly related to deeper bodies from the anomaly related to shallower bodies, regional-residual separation is performed by filtering or/and polynomial fitting mathematical processes (BELTRÃO *et al.*, 1991). Filtering occurs in the frequency domain, where structures closer to the surface present higher frequencies and their characteristic field is known as residual. The regional field is characteristic of deep bodies responsible for low frequencies in the data.

3.2 Direct 2-D modeling

The two-dimensional modeling technique used is based on Talwani *et al.* (1959), which allows lithological structures to be depicted by polygons and represented by profiles orthogonal to the anomaly direction. The calculation for the body volume is performed from the gravitational attraction caused by each vertex of the modeled polygon, so that the accuracy of the fit, as assessed by the interpreter, increases with increasing number of vertices of the polygon(s). The density contrast used to characterize the variations of this property must be constant for each polygon body in the initial model (TALWANI *et al.*, 1959).

Mathematically, a Cartesian coordinate system is adopted with origin at point P in the xz-plane, and the positive z-axis pointing vertically downward. In this geometry, one considers the angles between the xz-plane and a straight line connecting point P to the midpoint of each side of the polygon (θi), and the angle (ϑi) between vertex i and the xz-plane (TALWANI *et al.*, 1959). The vertical (ΔgZ) and Horizontal (Δgx) component of the gravitational attraction of an n-sided polygon and density ρ are calculated respectively according to equations 1 and 2 of Talwani *et al.*, (1959), where the parameters Zi and Xi are calculated from equations 3 and 4.

$$\Delta gz = 2G\rho \sum_{i=1}^{n} Z_i \quad (1)$$

$$\Delta gx = 2G\rho \sum_{i=1}^{n} X_i \quad (2)$$

$$Z_i = a_i \sin(\vartheta_i)\cos(\theta_i)\,[\theta_i - \theta_{i+1} + \tan(\vartheta_i)\, ln \frac{\cos(\theta_i)(\tan(\theta_i) - \tan(\vartheta_i))}{\cos(\theta_{i+1})(\tan(\theta_{i+1}) - \tan(\vartheta_{i+1}))}] \quad (3)$$

$$X_i = a_i \sin(\vartheta_i)\cos(\theta_i)\,\{\tan[\vartheta_i(\theta_{i+1} - \theta_i)] + ln \frac{\cos(\theta_i)(\tan(\theta_i) - \tan(\vartheta_i))}{\cos(\theta_{i+1})(\tan(\theta_{i+1}) - \tan(\vartheta_{i+1}))}\} \quad (4)$$

According to Blakely (1996), the big problem in modeling is to be able to represent the geology through geometric shapes with as much fidelity as possible and with minimum computational cost, hence, maximum initial geological information and the integration of geophysical methods in the interpretation of the region is essential.

3.3 2-D Inversion

The inversion methodology applied in this paper, produced by Silva *et al.* (2006), is based on the inverse modeling technique of Guillen *et al.* (1984), modified to allow the interpretation of anomalies caused by complex and interfering sources. This tool uses the observed gravity anomaly data, and initial specifications indicated by the interpreter. This information suggests the contours of anomalous sources in terms of geometric elements (line segments and points) and the density contrast associated with the geometric elements/sources.

The inverse model interpretation mesh is subdivided into juxtaposed 2-D prisms with constant density values to be determined, while the gravity anomaly curves are arranged along a profile perpendicular to the direction of the structure. The method then estimates the density contrast distribution that fits the observation within the experimental errors and represents compact sources closest to the specified geometric elements (SILVA *et al.*, 2006). The user has the power to modify the structure of the sources from changing parameters in the initial model entered and test models until there is a satisfactory fit of the generated model and an acceptable fit between the observed and calculated anomaly. The mathematical procedures involved are detailed in Silva *et al.* (2006).

The parameters applied to the meshes used in the 2-D inversions, for each gravity profile analyzed in the study, are shown in Table 01.

Table 01 - Specifications of the meshes used in the 2-D inverse modeling for each profile plotted.

Specifications of meshes used in 2-D inverse modeling				
Parameter	**Profile 1**	**Profile 2**	**Profile 3**	**Profile 4**
Length of the cell in x (km)	0,8	0,8	0,8	0,8
Length of the cell in z (km)	0,8	0,8	0,8	0,8
Number of cells in x	131	137	91	184
Number of cells in z	15	15	15	15

Source:Elaborated by the author (2020).

3.4 Magnetic method

The magnetic method is characterized by the detection of anomalies in the Earth's magnetic field, influenced by the varying rate of magnetic minerals in the composition of subsurface rocks. Thus, it uses magnetic field information to investigate subsurface structures, providing information such as geometry and depth of anomalous sources. In addition to identifying the sources, by processing the magnetic data, it is possible to delineate and map folds, faults, and other structures. In this paper, we use the information obtained from the linear transformation of the Analytical Signal Amplitude (NABIGHIAN, 1972), in order to identify and map in subsurface the dome structures of Girau do Ponciano and Itabaiana.

The magnetic data used in this work comes from the aeromagnetic survey 1102 ESTADO DE SERGIPE which belongs to the CPRM database, where the acquisition was made along parallel and equispaced flight lines in 500 m, with N-S flight direction. The control lines (tie-lines) were made perpendicular to the survey lines with 5 km spacing and E-W direction.

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4. Results and discussions

Once the gravity data was properly processed, a regional-residual separation was applied to the interpolated data, through the robust polynomial method of degree three (BELTRÃO *et al.*, 1991). This procedure was used to highlight the interesting structures for modeling, such as the Sergipe sub-basin and the Itabaiana and Girau do Ponciano domes (Figure 2). Thus, we obtained inverse and direct models of the set formed by the basement and the sub-basin, tracing four profiles along the region using geophysical and geological information of the interesting environments.

According to the gravity maps in Figure 2, we can observe the changes in anomalies due to regional-residual separation, varying the trends in some points of the map. A greater emphasis was given to the region with low gravity in the southeast portion of the map, which should be related to the sedimentary area of the Sergipe sub-basin. Another observation deduced through figure 2 is the disposition of the Girau do Ponciano dome in a high gravity region, indicating amplitudes of about 11.5 ± 1.0 mGal in the residual map.

As for the Itabaiana dome, it is found in a region that becomes less prominent after the regional-residual separation process, indicating values in the order of 0.2 ± 0.1 mGal, amplitudes not as expressive as in the structure mentioned above. The map of total Bouguer anomaly shows maximum and minimum values of 58.3 mGal and -37.3 mGal, while the map of residual Bouguer anomaly indicated amplitudes ranging from -39.1 mGal to 22.4 mGal, so it can be seen that there was an increase in negative anomalies and a reduction in the amplitude of positive anomalies after the separation performed.

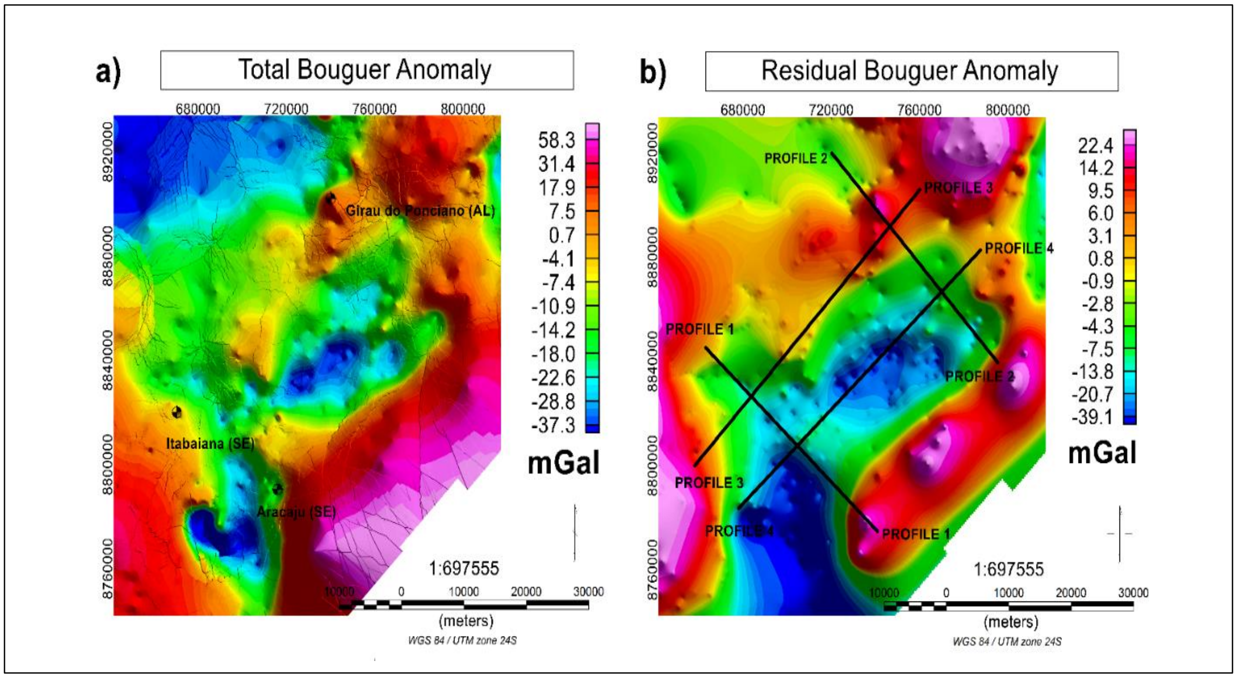

Figure 2 - a) Map of total Bouguer anomaly of the study region, indicating the cities of Aracaju, Itabaiana and Girau do Ponciano. b) Map of residual Bouguer anomaly of the study region, indicating the 4 profiles analyzed. Source: Elaborated by the author (2020).

The previous work by Sampaio *et al.* (2019) presents the distribution of density values for the study area. These values were obtained from rock samples collected in the field, and the averages of the property in question by geological domain were also acquired in this work (Figures 3 and 4).

In Figure 5, we have the representative map of the Analytical Signal Amplitude applied to the total anomaly magnetic field. In this image, it is possible to notice the magnetic signature of the Itabaiana dome in the southwest portion of the map, which presents amplitudes of about 0.07 ± 0.01 nT/m, standing out from its magnetically irrelevant surroundings. As for the Girau do Ponciano dome, its magnetic relief can be seen in the Northeast part of the map, located in a region of intense amplitudes, corresponding to geotectonic domains that present structures and shear zones, which are characterized as magnetic sources in evidence. Thus, the values corresponding to this dome are spare and of the order of 0.09 ± 0.01 nT/m.

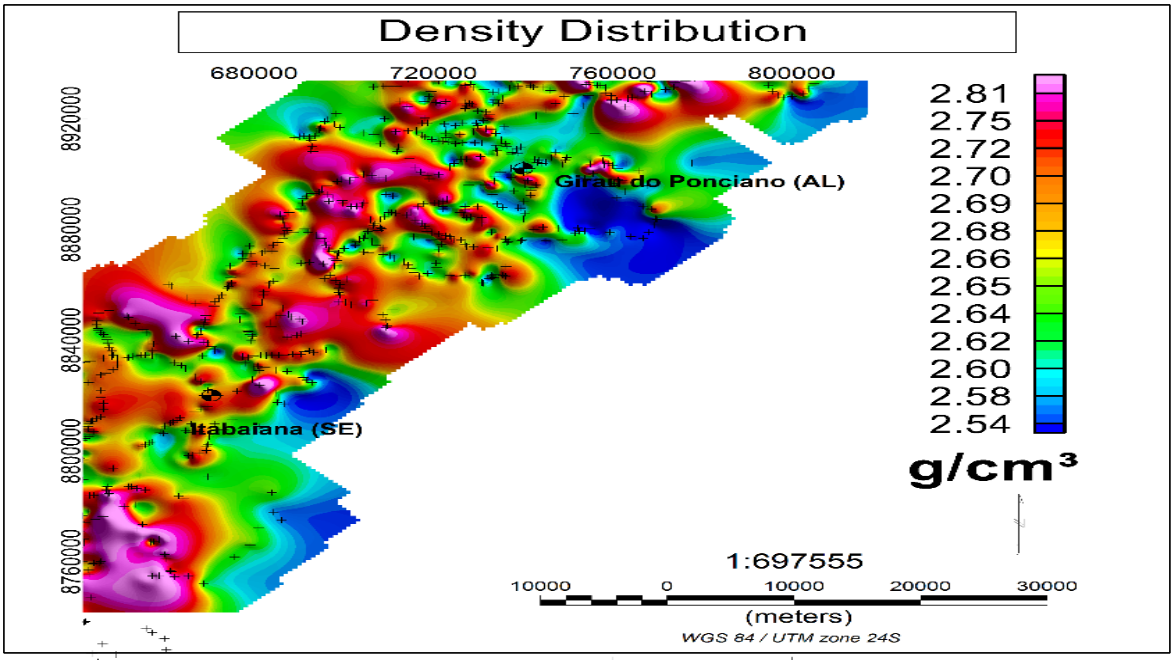

Figure 3 - Distribution of densities (g/cm³) of rock samples collected in the field (black points). Source: Elaborated by the author (2020).

In the evident points of the magnetic signatures of the domes, it is perceptible a spatial identification of continuity of the structure that goes beyond what is exposed in geological maps. Considering the sequential character of this signature as an indication of the subsurface sequence of the geological formation in discussion, we used contour information of the magnetic sources of interest, taken from the linear transformation seen in figure 5, thus helping the correct allocation of the profiles over the domes of Itabaiana and Girau do Ponciano. Thus, the four profiles were made and can be seen in figures 2 and 5, in the maps of residual Bouguer anomaly and amplitude of the analytical signal respectively.

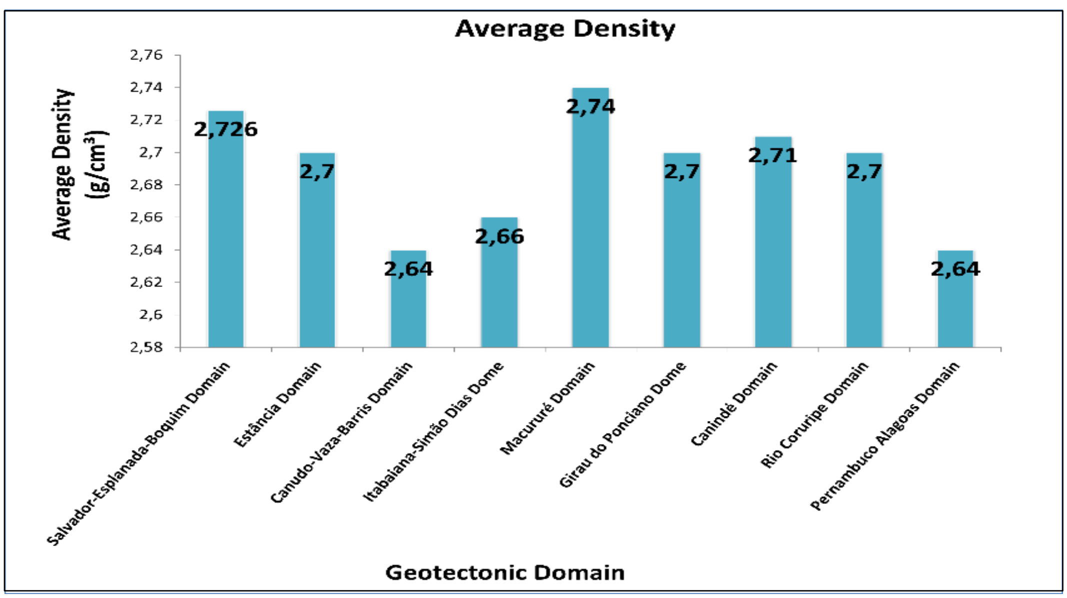

Figure 4 - Average density value (g/cm³) by geological domain. Source: Elaborated by the author (2020).

Profiles 1, 2, and 3 were purposely drawn over the domes, in view of the previous knowledge of geophysical and geological characteristics of such structures that helped in the modeling process. A simple comparison with Figure 1 shows the congruence between the shapes of the geological and magnetic contours of the domes, although Figure 5 presents additional information that geology cannot provide.

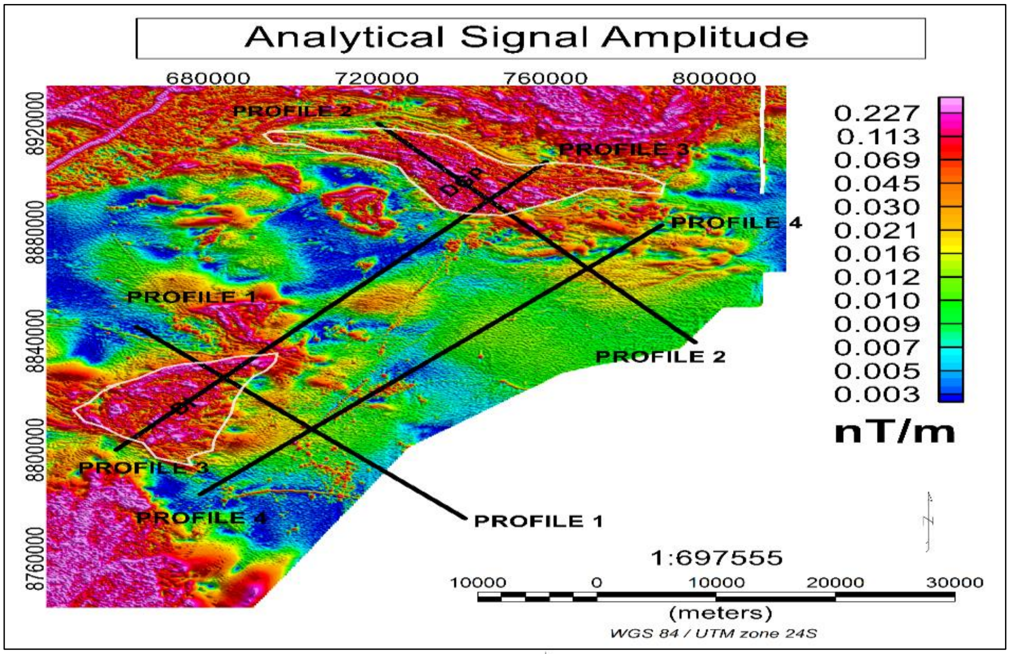

Figure 5 - Map of the amplitude of the Analytical Signal, showing the profiles drawn to perform the modeling with indication of the Itabaiana Domes (DI) and Girau do Ponciano Dome (DGP)
Source: Elaborated by the author (2020).

According to the disposition of the section defined as profile 1, it will correspond to the set basement + Itabaiana dome + Sergipe sub-basin, while profile 2 will approach the basement with focus on the Girau do Ponciano dome and the sub-basin. Profile 3 will show the region of the adjacent basement, crossing the dome structures, and profile 4 will show only the sedimentary region under study.

In possession of the gravity anomaly curves referring to the four profiles, the 2-D inverse modeling of the data was initiated, which relied on a priory geological information (SILVA *et al.*, 1995; BOEKER, 2011; SAMPAIO, 2019) to define the initial density contrasts of the known bodies, and geographic, to locate the sources of interest, and thus build the initial models to be inserted in the program used (SILVA *et al.*, 2006). In this process, the author used point shapes to represent the domes studied and lines to represent the average depth of the basement in the region of the profile, or in certain cases, the basin, through a line allocated on the surface. To make the inversion meshes of the profiles, the values for length and number of cells were employed, both vertically and horizontally, as shown in Table 01. The density contrast values used for the models inserted in each profile are found in Table 02.

The results of the 2-D inversion elaborated in this paper incorporeal to the geological information and jointly engaging the depth inverse model taken from Dutra et al. (2017), that in the results are corresponding to the 2 and 4 inverted profiles, thus in the direct gravity models are corresponding to the four profiles.

The density values used for each group/formation/geological structure present in these representations are arranged in Table 03. The orthogneissic domes of Itabaiana and Girau do Ponciano, besides the gneissic basement, were based on the data provided in the bibliography (SILVA *et al.*, 1995; BOEKER, 2011; SAMPAIO, 2019) according to their composition, while the Macururé and Canudos-Vaza-Barris domains correspond to the average density values among the groups/formations that compose them, as defined by Silva *et al.* (1995). The density related to the adjacent domains was chosen within the range established for the two domains present (2.62 to 2.71 g/cm³) in the region of profile 3.

Table 02 - Density contrasts used in the initial 2-D inversion models for each traced profile.

Density contrasts for 2-D inverse modeling (g/cm³)				
Geological structure	**Profile 1**	**Profile 2**	**Profile 3**	**Profile 4**
Basement	0,12	0,12	0,14	0,2
Sergipe Sub-Basin	-0,12	-0,12	X	-0,2
Itabaiana dome	0,12	X	0,2	X
Girau do Ponciano Dome	X	0,2	0,15	X
Identified Source (F1)	0,25	X	X	X

Source: Elaborated by the author (2020.

Table 03 - Densities used in the formations represented in the 2-D interpretive direct model referring to each profile drawn, respecting the data of this property arranged in Silva et. al (1995), Sampaio (2019) and Boeker (2011).

Densities used in direct 2-D modeling (g/cm³)				
Strutucture/ Formation	**Profile 1**	**Profile 2**	**Profile 3**	**Profile 4**
Itabaiana dome	2,67	X	2,67	X
Girau do Ponciano dome	X	2,82	2,8	X
Basement	2,82	2,86	2,85	2,82
Sergipe Sub-Basin	2,45	2,46	X	2,45
External sediments	2,6	2,6	X	2,6
Superficial sediments	X	2,3	X	2,3
Macururé domain	X	2,73	X	X
Canudos-Vaza-Barris domain	2,62	X	X	X
Adjacent domains	X	X	2,71	X

Source: Elaborated by the author (2020).

4.1 Profile 1 modeling

Profile 1 was drawn in a NW-SE direction, passing through the Itabaiana Dome and the southern portion of the Sergipe sub-basin, measuring about 104.7 km of extension. At the SE edge of the profile in question, a strong positive gravity anomaly can be perceived (Figure 2).

A distinct anomalous source is attributed to this section, where it is assumed by the geological context of the area, that it may be part of the northern region of the São Francisco Craton, accommodated under the sediments of the Sergipe sub-basin. Thus, to represent this identified source, named F1, a point geometric shape with a different density than the other structures represented was added to the initial model for the inversion.

Completing the initial model, the shapes representing the dome (point near the surface, due to its outcropping character), the basement (extensive straight line at 4.2 km depth) and the sub-basin (superficial straight line) were also inserted. The mesh parameters and density contrast values applied in the inversion are listed in Tables 01 and 02, respectively. The result obtained can be seen in Figure 6.

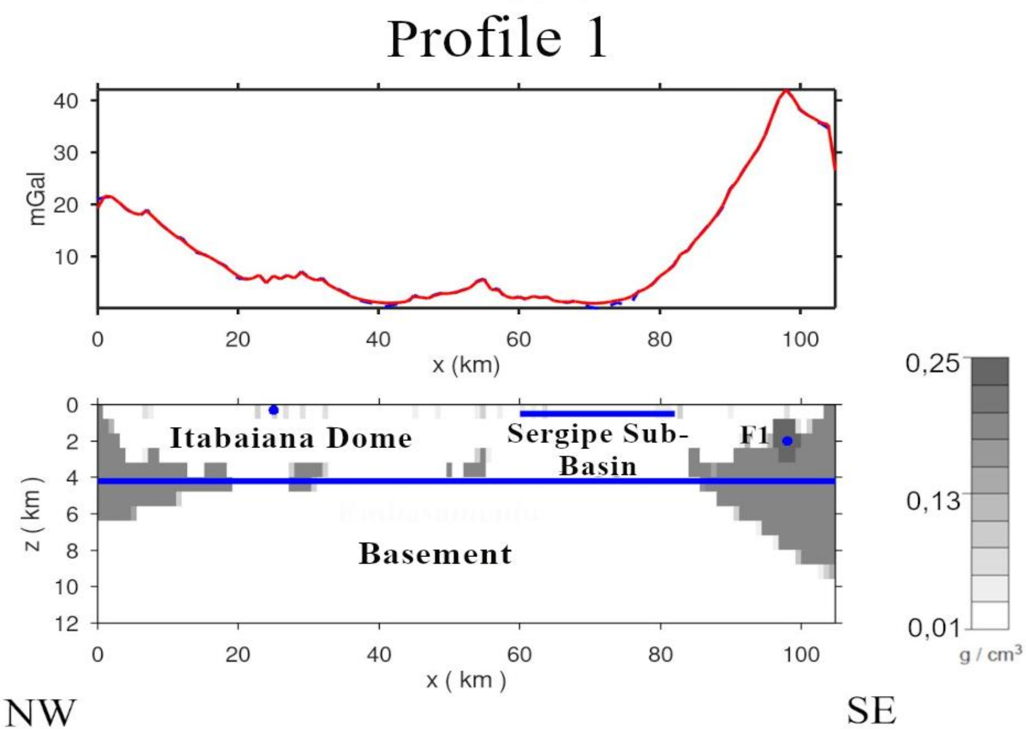

Figure 6 - Model resulting from the inversion of profile 1, where the substratum is represented by a mesh of juxtaposed 2-D prisms with each cell referring to a constant density contrast value. The red curve represents the observed anomaly and the dotted curve represents the anomaly calculated from the inverted model.
Source: Elaborated by the author (2020).

Observing the profile 1, we verify concentrations of high density contrasts at the edges and spaced along what is supposed to be the basement, it is still possible to identify a small variation of values near the representative point of the dome and a higher density contrast around F1. As for the geometry of the sources, we did not get much information, with the exception of the basal relief boundary at the edges, close to the surface. However, the curve fitted almost perfectly in this model, which induces a positive look at the chosen depth of the top of the basement, as well as the density contrasts of the bodies represented in the initial model. The recorded values ranged from 0.01 to 0.25 g/cm³ in this profile.

On the other hand, the resulting direct modeling (Figure 7) had an error of 0.740 mGal between the calculated and observed gravity anomaly curve. In the model, the Sergipe sub-basin was represented, allocated according to the geological data collected, the dome structure in question, represented by an outcropping body with an approximately oval shape, the top of the basement, maintained at an average depth of 4.0 km, sediments external to the basin, possibly fluvial (RANCAN *et al.*, 2008), and the Canudos-Vaza-Barris geotectonic domain, where the profile is inserted. According to this interpretation, the basement is deeper in the dome region, about 4.8 km, and shallower under the basin, which is kept at an average depth of 2.1 km. A maximum depth of 2.3 km can also be inferred for the Itabaiana Dome in this section. The density values used in each layer are shown in Table 03.

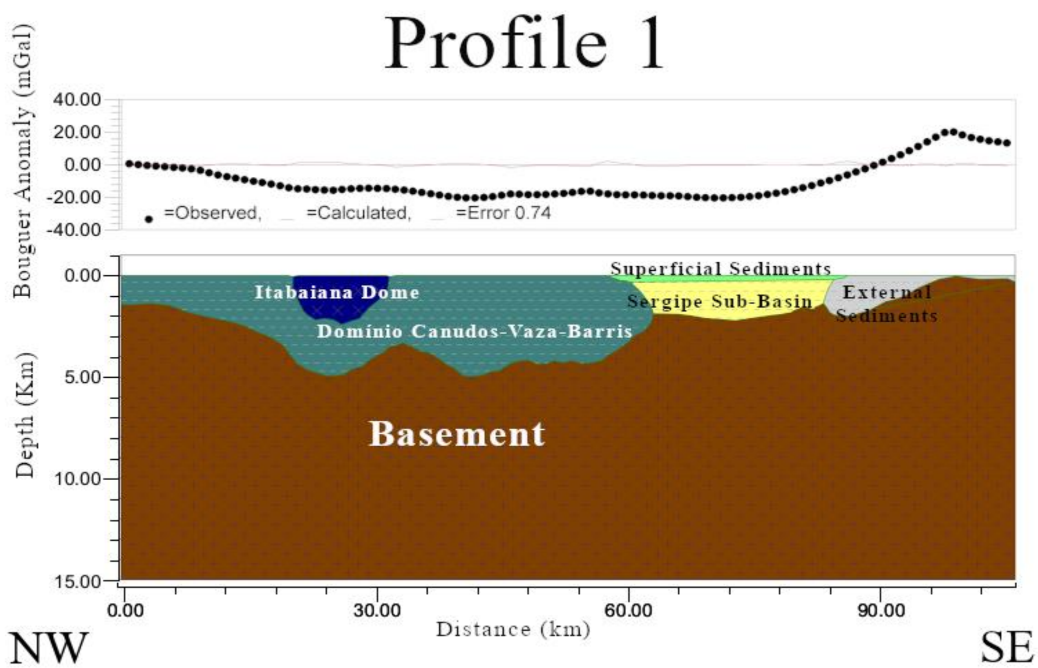

Figure 7 - Interpreted direct model of profile 1. The dotted curve represents the observed anomaly, the black curve represents the calculated anomaly, and the red curve represents the error between both anomalies. The substratum is represented by the mesh at depth and modified according to the interpreter's conclusion.
Source: Elaborated by the author (2020).

4.2 Profile 2 modeling

Profile 2 was drawn in the NW-SE direction, crossing the Girau do Ponciano dome and the northern portion of the Sergipe sub-basin, accounting for about 110.3 km of extension. To produce its inverse model, we inserted initial models representing the dome (point near the surface due to its outcropping character), the basement (long line at 5.6 km depth) and the sub-basin (superficial line). The mesh parameters and the density contrast values used in the inversion are shown in tables 01 and 02 respectively.

It is possible to identify concentrations of high density contrasts at the edges and other locations corresponding to high values of gravity anomaly, in the region where it is believed to be located the dome and the area under the basin, although with little expressiveness. The calculated anomaly curve fitted well to the observed anomaly, strengthening these potential initial models. We can also verify that in the region of the presumed location of the dome, it is not possible to identify variation in the values of density contrasts in the depth range corresponding to the basement, which may mean similar densities between these structures.

Within the basin region, we can model the negative density contrast changes and depth up to 1.8 km, so it can be assumed that the sedimentary framework of this area reaches at least this depth. As for the geometry of the sources, we were able to extract information about the upper limit of the basement and the Sergipe sub-basin that supported direct modeling. The recorded values range from -0.02 to 0.20 mGal. In Figure 9, we show the depth of the sediment-basement interface of the Sergipe sub-basin, according to the results of the gravity data inversion in Dutra *et al.* (2017). In this case, the depth response found by the inversion follows the lows of the Bouguer anomaly, denoting the low gravity signature usually observed in sedimentary basins.

The corresponding forward modeling of profile 2 (Figure 10) exhibited an error between the calculated and observed gravity anomaly curve of 0.830 mGal. In this model, we used the data obtained from the depth inversion performed in Dutra *et al.* (2017) (Figure 9), in which the sediments of the Sergipe sub-basin reach a maximum depth of 3 km. Thus, the direct modeling represented the sedimentary framework with a depth of 2 to 3 km in its extent, presenting a similar geometry to the inverse models derived.

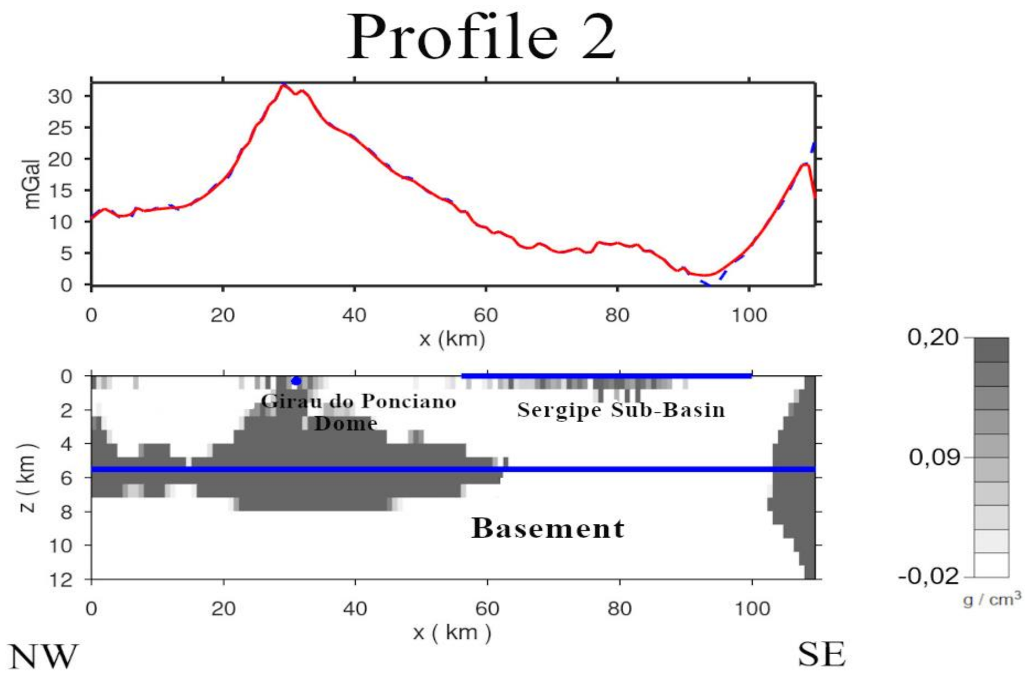

Figure 8 - Model resulting from the inversion of profile 2, where the substratum is represented by a mesh of juxtaposed 2-D prisms with each cell referring to a constant density contrast value. The red curve represents the observed anomaly and the dotted curve represents the anomaly calculated from the inverted model.
Source: Elaborated by the author (2020).

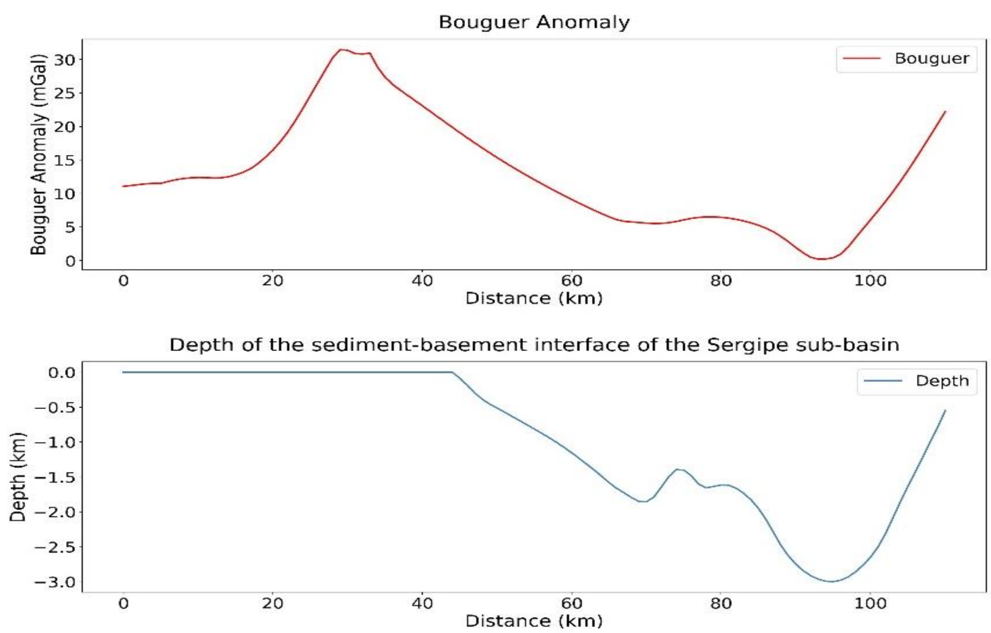

Figure 9 - Curves representing the Bouguer anomaly, in red, and the depth of the sediment-basement interface of the Sergipe sub-basin, in blue, according to the results of the inversion performed in Dutra et al. (2017) referring to profile 2. Source: Elaborated by the author (2020).

The Girau do Ponciano dome was interpreted with a depth range until 6 km, presenting a density close to the basement (Table 03), as supposed by the inversion model. The basement was also reproduced, deeper in the region corresponding to the dome, similar to the inversion model in this part of the profile, and shallower in the basin region, with similar average depths between the inverse and forward models. The sediments external to the sub-basin, the surface sediments/coverings indicated by the geology, and the Macururé domain, where the profile is inserted, were also represented. The density values used are shown in table 03.

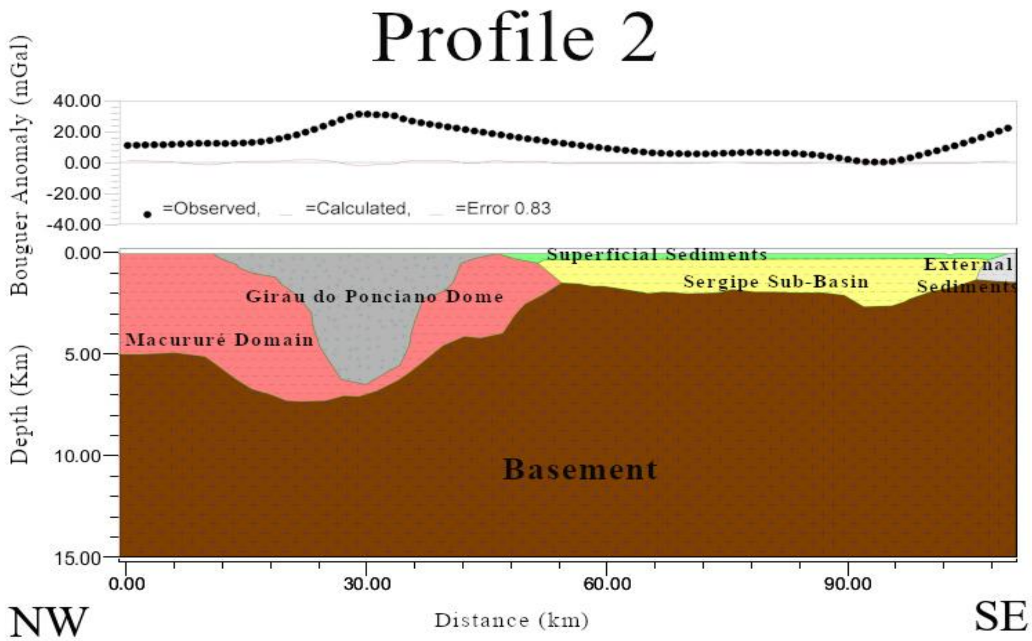

Figure 10 - Interpreted direct model of profile 2. The dotted curve represents the observed anomaly, the black curve represents the calculated anomaly, and the red curve represents the error between both anomalies. The substratum is represented by the mesh at depth and modified according to the interpreter's conclusion.
Source: Elaborated by the author (2020).

4.3 Profile 3 modeling

Profile 3 was drawn in SW-NE direction, crossing the Itabaiana dome to the south and the Girau do Ponciano dome to the north, with a length around 145.8 km. In order to obtain the inverse model, the data was divided in two parts to facilitate the inversion process, since the results obtained in the inverse modeling of the complete profile were not efficient.

The first section corresponds from kilometer zero to 74, while the second goes from kilometer 74 to 145. Thus, in the initial fragment (Figure 11a) the Itabaiana dome (point near the surface) and the basement (long straight line at 5.0 km depth) were represented, finding higher density contrast values near the edges along the basement and small concentrations of higher amplitudes around the dome. The anomalous curves fitted very well and the contrasts ranged from -0.01 to 0.15 g/cm³.

In the second fragment (Figure 11b), the final inverse modeling had the representation of the basement (long straight line at 5.0 km depth) and the Girau do Ponciano dome (point on the surface). High density contrast values were highlighted throughout the extent of the basement, efficiently fitting the curves between the anomalies from the initial models used. The amplitudes ranged from 0 to 0.20 g/cm³ in this section.

The density contrast values and mesh parameters used in the inversion are shown in Table 01 and 02 respectively. As for the geometry, we took information from the basal upper limit to aid the forward modeling of this profile. The direct modeling of profile 3 (Figure 12) showed an error between the calculated and observed gravity anomaly curve of 0.744 mGal. The interpretation exposed in this model disposes the Itabaiana and Girau do Ponciano dome in a congruent way to the basement shape, both reaching about 4 km depth.

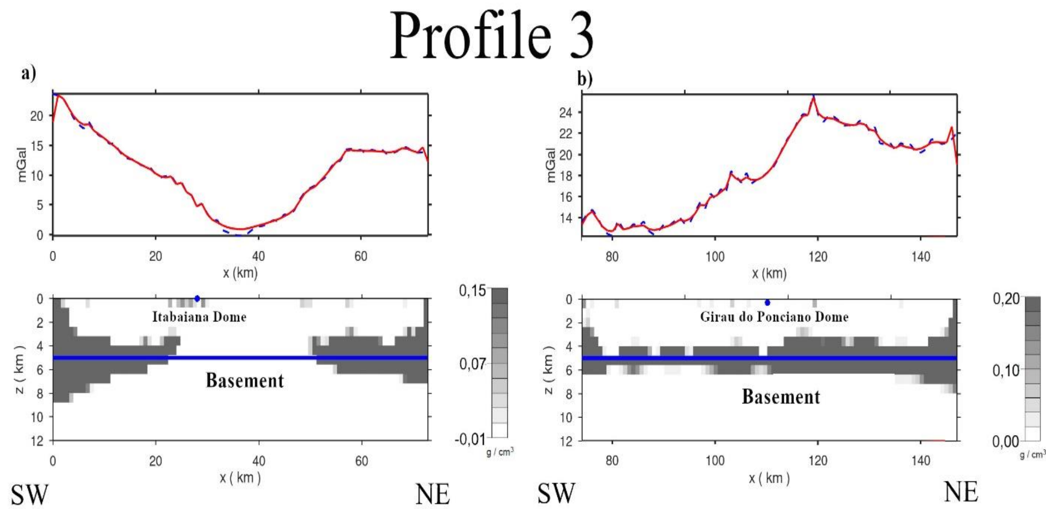

Figure 11 - a)Model resulting from the inversion of profile 3a, covering the Itabaiana Dome region, where the substratum is represented by a mesh of juxtaposed 2-D prisms with each cell indicating a constant density contrast value. The red curve represents the observed anomaly and the dotted curve represents the calculated anomaly from the inverted model. b)Model resulting from the inversion of profile 3b, covering the region of the Girau do Ponciano dome, where the substratum is represented by a mesh of juxtaposed 2-D prisms with each cell indicating a constant density contrast value. The red curve represents the observed anomaly and the dotted curve represents the anomaly calculated from the inverse model
Source: Elaborated by the author (2020).

The basement presented an average depth of 5 km, as in the inverse models, being deeper in the regions under the domes. Finally, because the profile covers the region of two different tectonic domains, we represented the sedimentary framework of the region as an adjacent domain, presenting a single density.

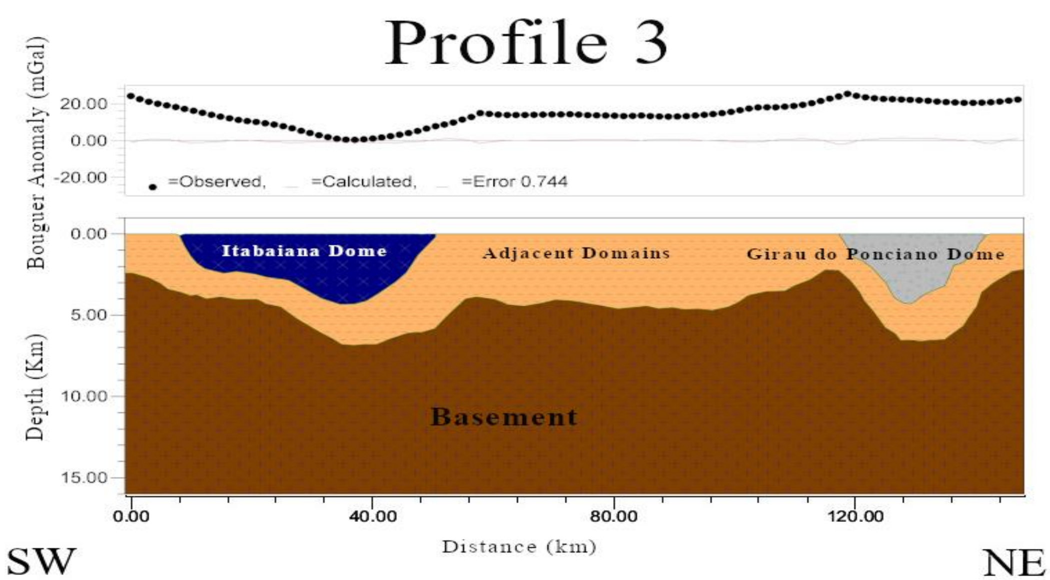

Figure 12 - Interpreted direct model of profile 3. The dotted curve represents the observed anomaly, the black curve represents the calculated anomaly, and the red curve represents the error between both anomalies. The substrate is represented by the mesh at depth and modified according to the interpreter's conclusion.
Source: Elaborated by the author (2020).

4.4 Profile 4 modeling

The profile 4 was drawn in an SW-NE direction, crossing the entire Sergipe sub-basin, accounting for about 147 km in length. The initial models inserted in the inversion represented only the basement as an extended straight line at 4.2 km depth, resulting in Figure 13. The density contrast values and mesh parameters used in the inversion are shown in table 01 and 02 respectively.

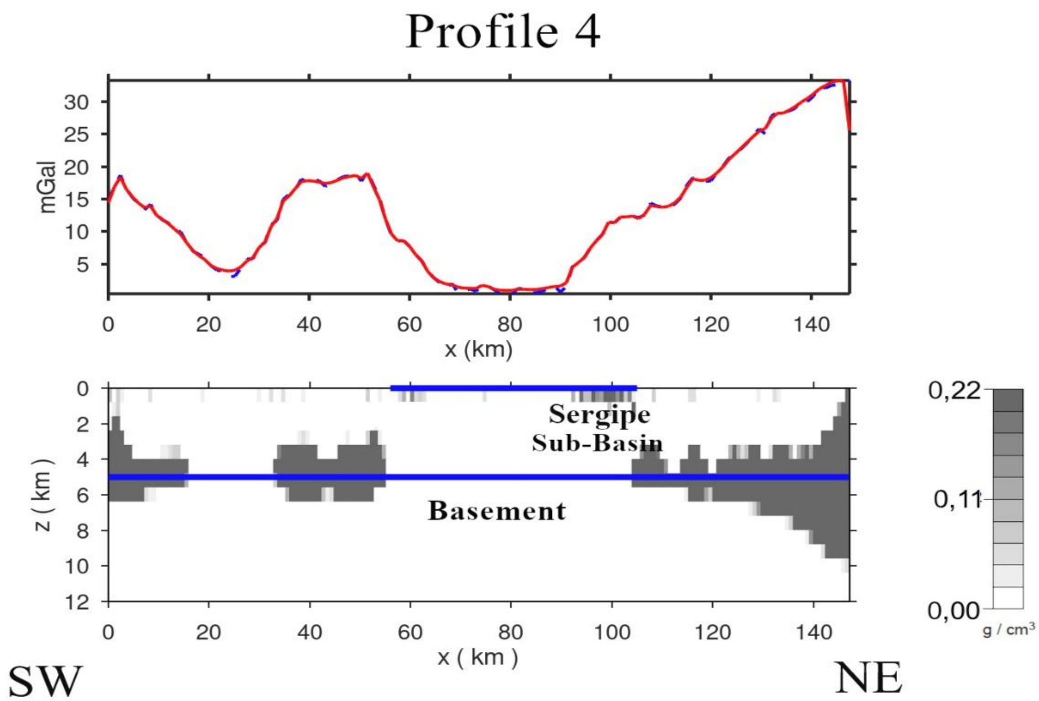

Figure 13 - Model resulting from the inversion of profile 4, where the substratum is represented by a mesh of juxtaposed 2-D prisms with each cell indicating a constant density contrast value. The red curve represents the observed anomaly and the dotted curve represents the anomaly calculated from the inverted model.
Source: Elaborated by author (2020).

The result obtained demonstrated density contrast values concentrated under the Bouguer anomaly highs at the basement level, while few density contrast variations were highlighted near the Sergipe sub-basin. The initial models caused a good fit between the calculated and observed anomaly curves, showing maximum and minimum density contrast values of 0.22 and 0 g/cm³ respectively.

The direct modeling resulting from profile 4 (Figure 15) presented an error between the calculated and observed gravity anomaly curve of 0.524 mGal. As in profile 2, we used the data obtained from the depth inversion carried out in Dutra *et al.* (2017) (Figure 14), in which the sediments of the Sergipe sub-basin reach a maximum depth of 4 km. By analyzing the anomaly curve, comparing it with the representation of the sediment-basement interface, it is possible to notice the similarity between the two highlighted contours, thus evidencing the pattern of gravity lows usually related to sedimentary basins. It can also be seen that the greater the depth found, the more negative the anomaly.

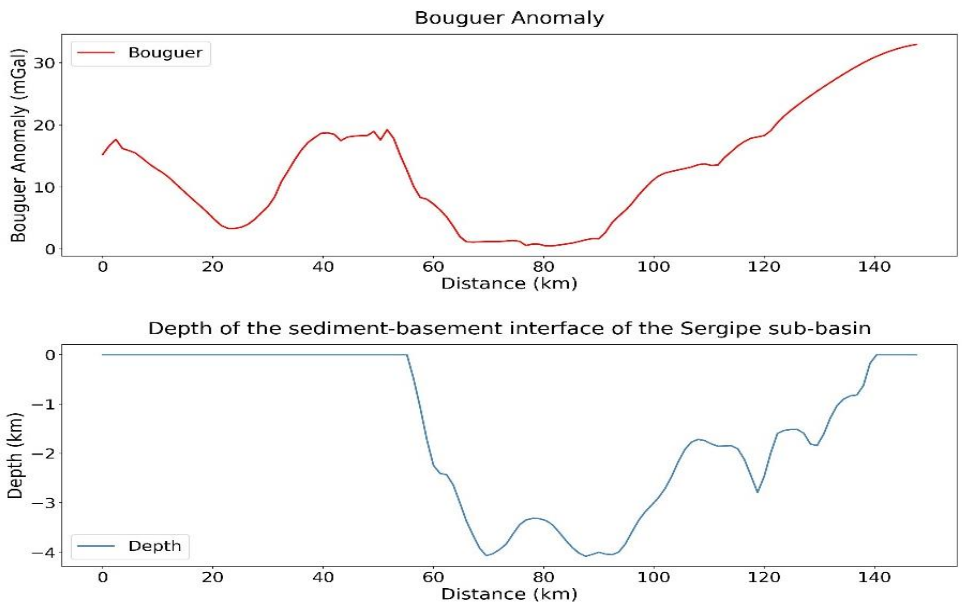

Figure 14 - Curves representing the Bouguer anomaly, in red, and the depth of the sediment-basement interface of the Sergipe sub-basin, in blue, according to the results of the inversion performed in Dutra et al. (2017) referring to profile 4. Source: Elaborated by the author (2020).

Therefore, following the pattern of this curve and using a maximum depth for the Sergipe sub-basin of 3.8 km, the sedimentary framework was modeled and represented with a covering of superficial sediments, indicated by the geology. Besides these formations, the basement, whose top maintained an average depth equivalent to that used in the inversion of 4.2 km, and the sediments external to the sub-basin were exposed. The density values used are in Table 03.

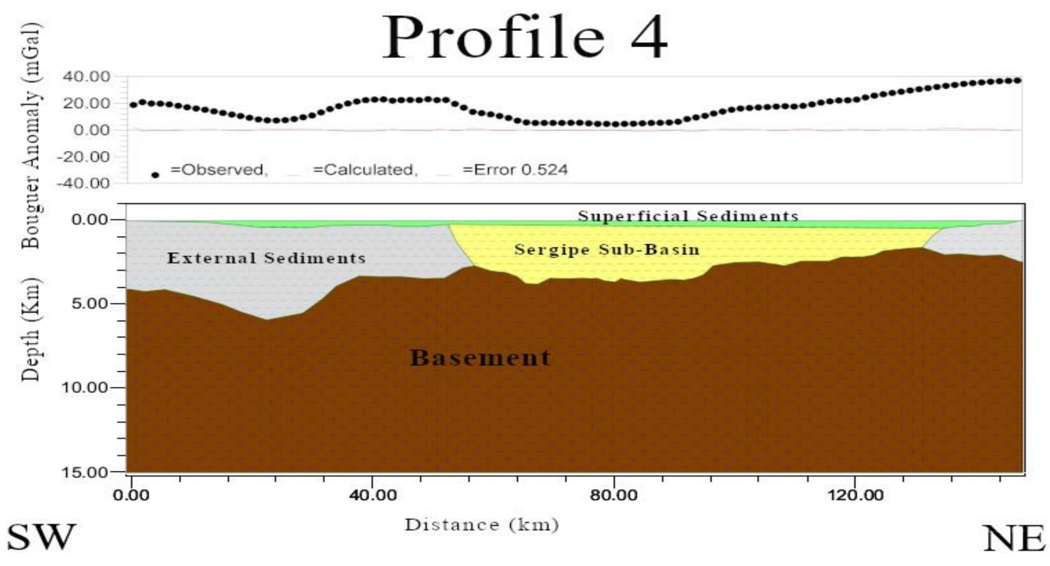

Figure 15 - Interpreted direct model of profile 4. The dotted curve represents the observed anomaly, the black curve represents the calculated anomaly, and the red curve represents the error between both anomalies. The substratum is represented by the mesh at depth and modified according to the interpreter's conclusion.
Source: Elaborated by the author (2020).

5. Final remarks

In this paper, subsurface models of the Sergipe sub-basin region and its adjacent basement were presented, obtained from the inversion and direct modeling of four profiles drawn over the residual Bouguer anomaly map. To delineate the sections used, the magnetic map was efficiently employed, aiming the study of the adjacent basement in conjunction with Itabaiana and Girau do Ponciano dome structures in the region. Using the known gravity anomaly curves, inverse models were produced that provided important information about geometry, depth, and density contrast in the subsurface. In some cases, such information supported the next step of direct modeling. The direct models acquired promoted the geological interpretation of the defined sections, exposing the geological limits between the formations, the geometry of the main sources exposed in the scope of the work, and the densities associated with them. Observing the 4 interpreted profiles, the Sergipe sub-basin showed maximum depths of the sediment-basement interface of 2.3 to 3.8 km, while in the portion adjacent to it, the top of the basement remained at an average depth of about 5 km. For the Itabaiana and Girau do Ponciano domes maximum depths of 4 km and 6 km respectively were found along the analyzed profiles.

The results of both models, direct and inverse, presented excellent fits between the observed and calculated gravity anomaly curves, qualifying the interpretations obtained. Thus, it is concluded that both methods provided good results, consistent with the local geology, delineating the relief of the adjacent basement and the Sergipe sub-basin. The information exposed in the article can be used for future works in the region that require this knowledge, such as an eventual thermomechanical modeling of the basin in question.

Acknowledgements

We acknowledge Promob - Cenpes - Petrobras for the support through the Petrobras project 0050.0082543.13-9, CPRM and ANP for the data provided, UFBA and the PERMANECER project for the research grant awarded. The authors would also like to thank the reviewer of the journal for the great suggestions provided.

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