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GEOSCIENCES

3D gravity modelling of areas under the aptian lakes in the Jatobá basin and Tucano Norte sub-basin – Negra and Tonã hills

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Abstract: Due to structural similarities and the possibility of connection between the two Aptian paleolakes in the Jatobá Basin and the Tucano Norte Sub-basin in Northeastern Brazil, the influence of the architecture of the crystalline basement under these lacustrine sedimentary rocks was analysed using gravimetric data near the faulted edges of the basins where the paleolakes are located. The Negra (Jatobá Basin) and Tonã (Tucano Norte Sub-basin) Hills are mainly sedimentary deposits of Aptian age and are linked to the post-rift I tectonic sequence. Aiming at the study of reservoirs analogous to pre-salt reservoirs, the gravimetric data were processed and interpreted to define the structural framework of the basin regions around these hills. Depth maps and density models were generated that could be analysed from various 3D perspectives, and the behaviour of the crystalline basement below these sedimentary sequences was investigated. In addition to the identification of horsts and semi-grabens that influenced the current relief pattern, the modelling showed that the Aptian paleolake sedimentary rocks of the Negra Hill are in the Ibimirim Low, which is approximately 2,900 m deep, while in the Tonã Hill, the sedimentary rocks are in the Salgado do Melão Low, which is approximately 5,100 m deep.

Key words: Aptian lakes, gravimetric modelling, Jatobá basin, Tucano Norte sub-basin.

INTRODUCTION

The Jatobá Basin and the Tucano Norte Sub-basin have sedimentary deposits of Aptian age that are linked to a post-rift tectonic sequence (Aragão & Peraro 1994). These sedimentary rocks are extensively studied in Brazil and worldwide because they were deposited in a time window when the largest hydrocarbon deposits ever recorded formed, including those in pre-salt layers (Mello et al. 1995, 2009a, b, Fontes & Zalan 2014, ANP 2020). During the Aptian, the fluvial lake sediments of the Marizal, Crato, and Romualdo Formations were deposited in the Jatobá Basin; however, the Romualdo Formation is not observed in the Tucano Norte Sub-basin (Varejão et al. 2016).

Due to the relevance and characteristics of these formations, a gravimetric study was carried out to analyse the behaviour of the crystalline basement below the Aptian sequences that are located in the Tonã (Tucano Norte Sub-basin) and Negra hills (Jatobá Basin) regions (Figure 1). Thus, this research was directed towards understanding the behaviour of the crystalline basement in terms of its influence on the current relief pattern and the absence of Romualdo Formation in the Tucano Norte Basin. The gravimetric method has been applied to the study of sedimentary basins for hydrocarbon

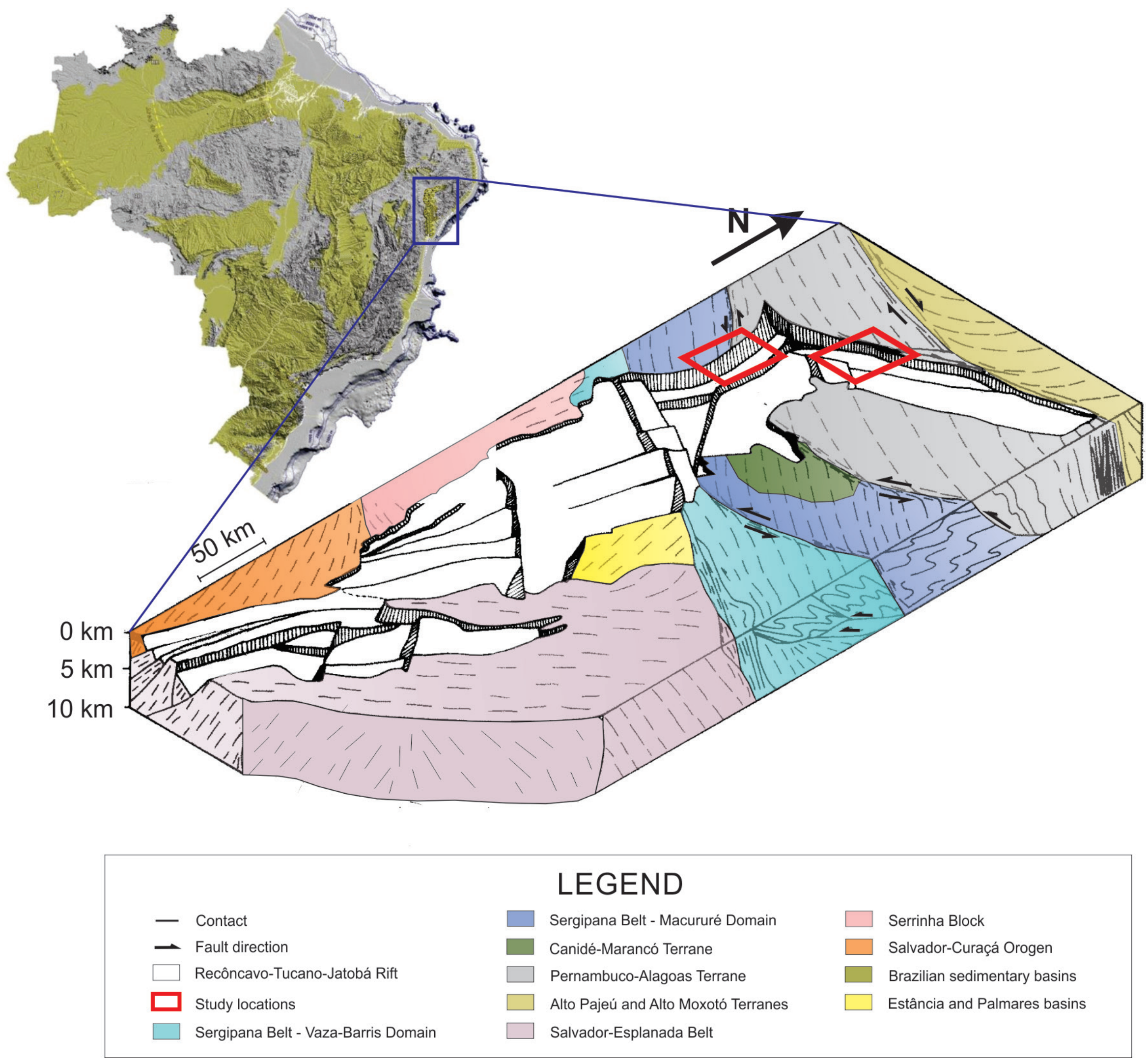

Figure 1. Architecture and structures of the Recôncavo-Tucano-Jatobá Rift basement (adapted by Milani & Davison 1988, modified from Milani et al. 2007).

exploration (e.g., Gaino et al. 2013, Castro et al. 2014, Constantino et al. 2019), geological mapping, mineral resource research (e.g., Ford et al. 2007, Airo 2015) and understanding of the Earth's crustal structures (e.g., Gibb et al. 1983, Karner & Watts 1983, White et al. 2005, Mishra & Ravi Kumar 2014, Oliveira & Andrade 2014, Oliveira & Medeiros 2018). The importance of the gravimetric method in oil exploration is associated the easy identification of vertical faults and sedimentary thickness due to its fairly routine process and easy application. Therefore, the method is widely used in the identification of tectonic depressions and in the modelling of sedimentary basins (e.g., Gaino et al. 2013, Castro et al. 2014, Constantino et al. 2019, Pinto & Vidotti 2019, Bessoni et al. 2020).

In this research, based on the proven ability of the gravimetric method to reveal the basement shapes and tectonic structures of sedimentary basins, modelling procedures were performed to define the three-dimensional framework of the two study regions. Thus, it was possible to locate faults, observe and correlate structures, and finally approximate the thickness of the sedimentary sequences. The results serve to expand the knowledge of basins and to identify new correlations with analogous pre-salt reservoirs.

Geological setting

The Jatobá Basin and Tucano Norte Sub-basin are part of the Recôncavo-Tucano-Jatobá Rift, which, according to Milani & Davison (1988), consists of several asymmetric grabens that are separated by basement highs and transfer faults (Figure 1), allowing the formation of five basins/sub-basins (Recôncavo, Tucano Sul, Tucano Central, Tucano Norte and Jatobá).

The Tucano Norte Sub-basin has an N-S orientation, measures approximately 100 km in length and 80 km in width on average, and is limited to the south by the Jeremoabo Fault and the Vasa Barris arch. The Jatobá Basin has a longitudinal direction close to N70° with a length of approximately 200 km and an average width of 40 km, which turns substantially towards the ENE.

The Serra Negra, with an altitude above 1,000 m, represents the most prominent geomorphological feature of the Jatobá Basin. It is located close to the fault at the edge of the basin and consists of Aptian and Albian sedimentary rocks linked to the post-rift I and post-rift II opening phases of the Atlantic Ocean (Neumann & Rocha 2014). Following the stratigraphic division and sedimentary succession proposed by Neumann et al. (2010), from bottom to top, the Aptian sequence (post-rift I) is formed by the sedimentary rocks of the Marizal, Crato and Romualdo Formations.

Like Serra Negra, Serra do Tonã represents the most prominent geomorphological feature in the Tucano Norte Sub-basin. It has a slightly steep morphological structure, a plateau shape, and a general N-S orientation. It also corresponds to a hill that contains the post-rift sedimentary sequence covered by unconsolidated quaternary sediments, resulting from its erosion and remobilization. Two stratigraphic intervals related to Serra do Tonã are present: the first interval corresponds to the Marizal Formation, which begins with a “sharp layer” exposed at the mountain’s base. The second interval is related to the carbonate sequence of the top of Serra do Tonã that is exposed in laminated limestone plates, which is called the Crato Formation (Silveira et al. 2014, Varejão et al. 2016).

MATERIALS AND METHODS

The gravimetric data that were processed and interpreted in this work were acquired by PETROBRAS and distributed for public use by the Brazilian National Bank of Gravimetric Data of the Brazilian National Petroleum Agency (Banco Nacional de Dados Gravimétricos -BNDG - Agência Nacional de Petróleo - ANP).

The altitudes and positioning of the stations were defined using topographic surveys. The absolute gravity values referenced the IGSN-71 (International Gravity Standardization Net – 1971).

The calculation of Bouguer anomalies was referenced to sea level with the density of the topography equal to 2.67 g/cm^3. Then, the data were interpolated in a 0.5 x 0.5 km grid using the minimum curvature method. The 2.5D modelling of the Bouguer anomaly profiles was performed by the direct method using the algorithm developed by Talwani et al. (1959), and Talwani & Heirtzler (1964) and implemented on the GM-SYS® platform integrated with Geosoft® Oasis Montaj software. After this stage, the profiles were grouped in a single database for each basin. The depth values were interpolated by the Tinning method in a 0.5 x 0.5 km grid, generating depth maps and density models that could be analysed from various three-dimensional perspectives.

Density contrast between sediments and crystalline basement

In the modelling process, a value of 2.35 g/cm^3 was set for the density of sedimentary rocks and, 2.80 g/cm^3 was set as the value for crystalline basement rocks, according to Telford et al. (1990). After establishing these density values for each set, a density contrast of 0.45 g/cm^3 was obtained between crystalline and sedimentary rocks. The obtained results showed that the chosen density represents an adequate average for the different types of rocks in the basin.

Regional-residual separation of gravimetric data

For the regional-residual separation of gravimetric data, the spectral separation technique was employed using of the Fourier transform. Gaussian filters applied in the wavenumber domain separates the original data into long-wave components (deep sources) and short-wave components (shallow sources). Using of this method, it was possible to observe the locations of the faults that define the tectonic framework of the basins in the short-wave component (residual). However, the residual component representative of the sedimentary rocks pile separated by this spectral method does not preserve the amplitudes of the anomalies, impairing the execution of quantitative models. Thus, the separation of the residual component was adopted by removing a 1st-order trend surface.

2.5D gravimetric modelling

The gravity modelling was carried out on 21 profiles in the Jatobá Basin and 25 profiles in the Tucano Norte Sub-basin. To obtain a good correspondence between the amplitude of the anomalies and modelling results, cross-sectional profiles of the longest length of the Bouguer negative anomaly were chosen (Figure 2). The steps of the modelling process were as follows:

1- Construction of two-dimensional models of the Jatobá Basin and Tucano Norte Sub-basin considering the trend surface of the Bouguer anomaly in the two basins;

2- Calculation of the effects of anomalies;

3- Comparison of the calculated effects with the observed data;

4- Adjustment of the calculated gravimetric profile to the observed data profile by changing the basin internal geometry in the model.

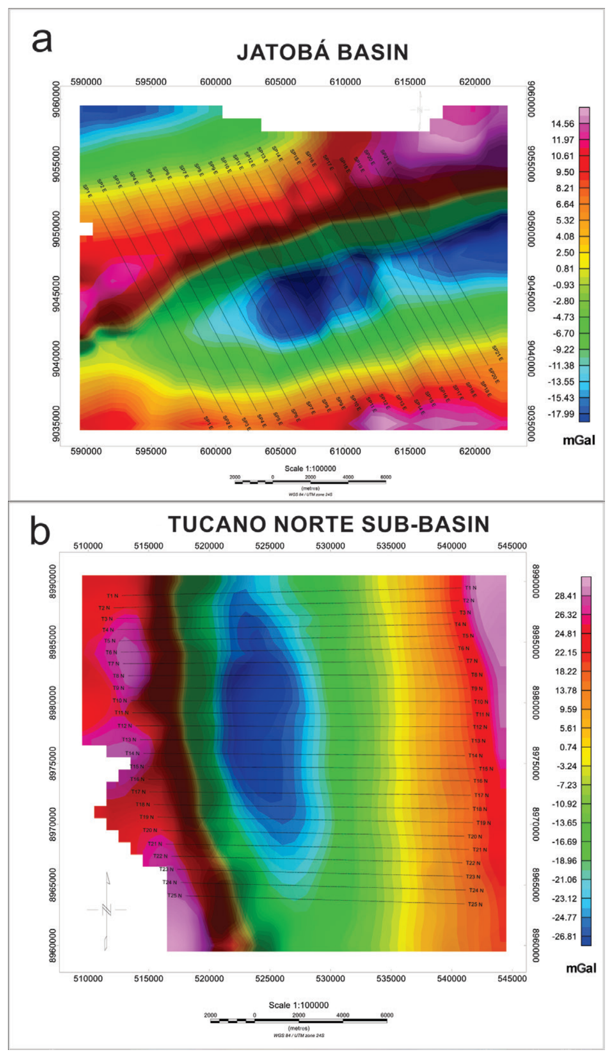

Figure 2. Trend surface maps of the Bouguer anomaly in the study region in the Jatobá Basin (a) and Tucano Norte Sub-basin (b), with the locations of the profiles selected for 2.5D modelling.

During these procedures, relevant geophysical and geological information such as seismic profiles and stratigraphic wells from works cited in this manuscript were considered.

Three-dimensional model

The modelling described in the previous section provided only a two-dimensional view of several sections of the basins (Figures 3 and 4). Obtain a three-dimensional view of the sets of 21 and 25 parallel sections modelled in the Jatobá Basin and Tucano Norte Sub-basin. The profiles were grouped into a single database for each basin. After this stage, the Tinning method interpolated the depth values in a 0.5 x 0.5 km grid.

RESULTS

In the Jatobá Basin, Bouguer anomaly values showed a maximum variation of 67.8 mGal (between -16.0 and -83.8 mGal). In the Tucano Norte Sub-basin, the maximum variation in the Bouguer anomaly is 85.9 mGal (between -32.3 and -118.2 mGal). The most positive values on the maps are concentrated in outcrops of the crystalline basement, at the edges of the basins and, outside their limits. The most negative values are concentrated within the limits of basins where sedimentary rocks and main depocentres dominate.

The Jatobá Basin depocentre, located in the main study area of this basin, is associated with a negative Bouguer anomaly, which has irregular to semi-circular shape, a slight elongation in the E-W direction, and a maximum amplitude of 12.8 mGal (between -71.0 and -83.8 mGal) (Figure 5b). In the Tucano Norte Sub-basin, the depocentre is correlated with a negative Bouguer anomaly axis stretched in the N-S direction, with a maximum amplitude of 6.2 mGal (between -112 and -118.2 mGal) (Figure 5b).

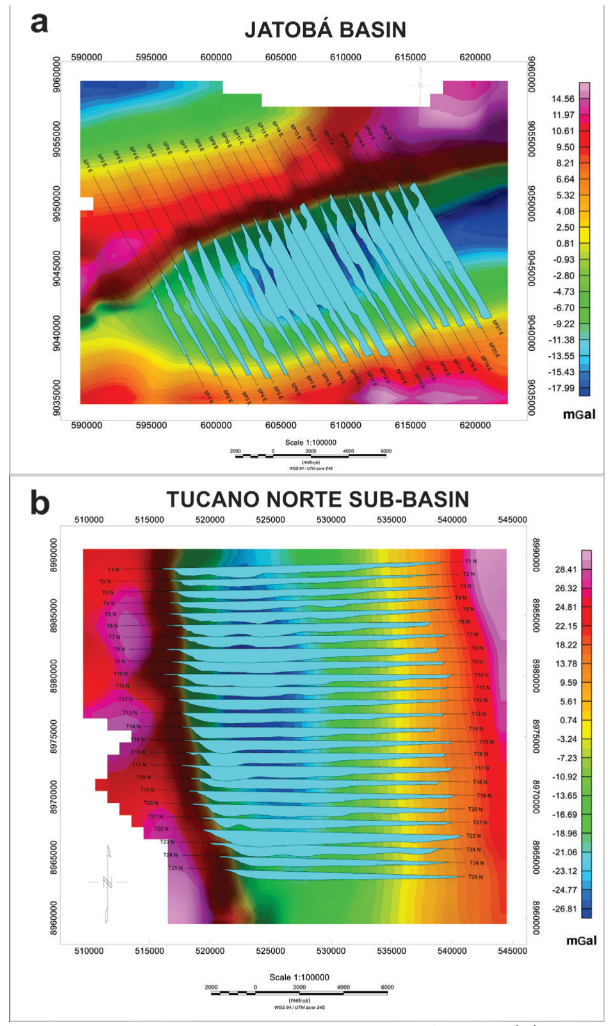

Figure 3. 2D depth profiles of the Jatobá Basin (a) and Tucano Norte Sub-basin (b).

As much is already known about these basins (Milani & Davison 1988), it is possible to confirm that the negative Bouguer anomaly in the Jatobá Basin has a very intense northwest gradient, while in the Tucano Norte Sub-basin, this gradient is located in the west. This type of anomalous conformation in sedimentary basins suggests that the sediments were deposited in a semi-graben tectonic structure, with a faulted edge (to the northwest in the Jatobá Basin and in the west in the Tucano Norte Sub-basin) and a flexural edge (southeast of the Jatobá Basin and east of the Tucano Norte Sub-basin).

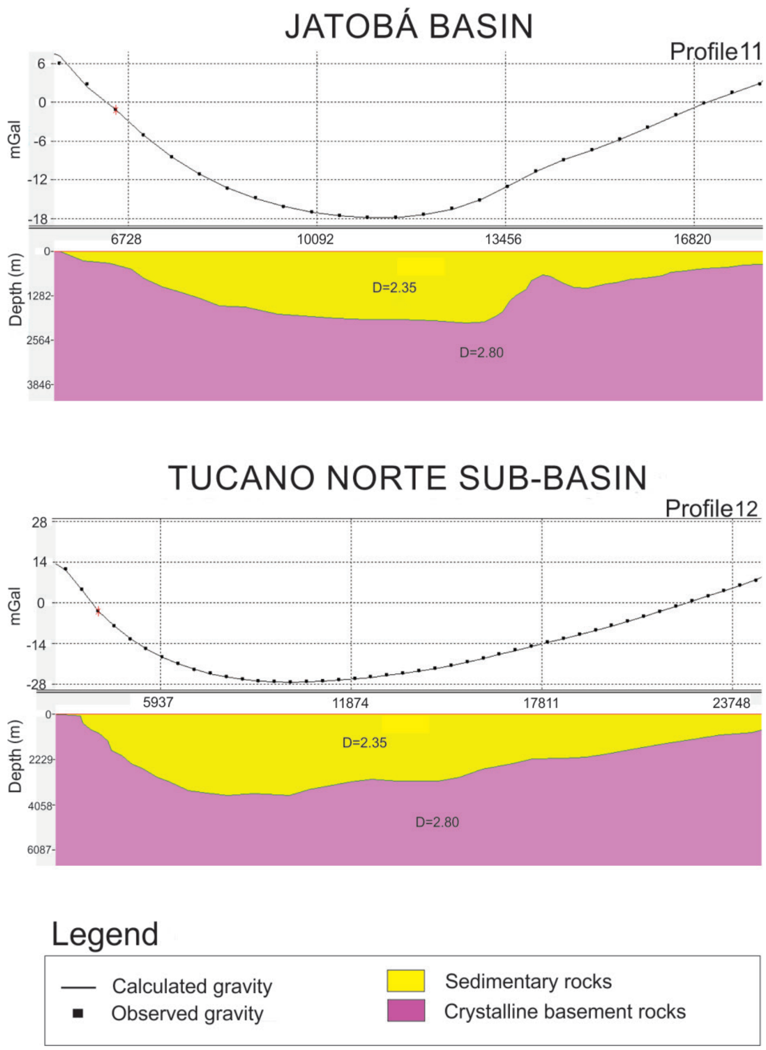

Figure 4. **2.5D density profiles of sections 11 and 12 (Jatobá Basin and Tucano Norte Sub-basin, respectively) modelled by the direct method.**

The results of the regional-residual separation of the gravimetric data are presented in Figure 6 and were used to interpret the faults that define the tectonic framework of the basins. It is possible to identify structures in the Bouguer Residual maps as normal faults (including basin faulted edge) and shear zones in both basins.

The results of the three-dimensional modelling can be visualized in the depth maps and the density models at four different angles of perspective in 3D (Figures 7 and 8). In addition, the presence of horsts and semi-grabens within the basins is observed in the regions where the Serra Negra and Tonã are located (Figure 9). These structures raise the hypothesis that the mountains were formed during a possible reactivation of the crystalline basement, resulting in the partial uplift of these blocks, since the seismic and outcrop data of the region indicate that these are normal domino faults within the Jatobá Basin, as described by Lima et al. 2015.

The generated three-dimensional models demonstrate that the study areas in both basins have shapes similar to those of semi-grabens, with a missing main edge and deep depocentres, and reach approximately 2900 m and 5100 m in the Jatobá and Tucano Norte Sub-basins, respectively.

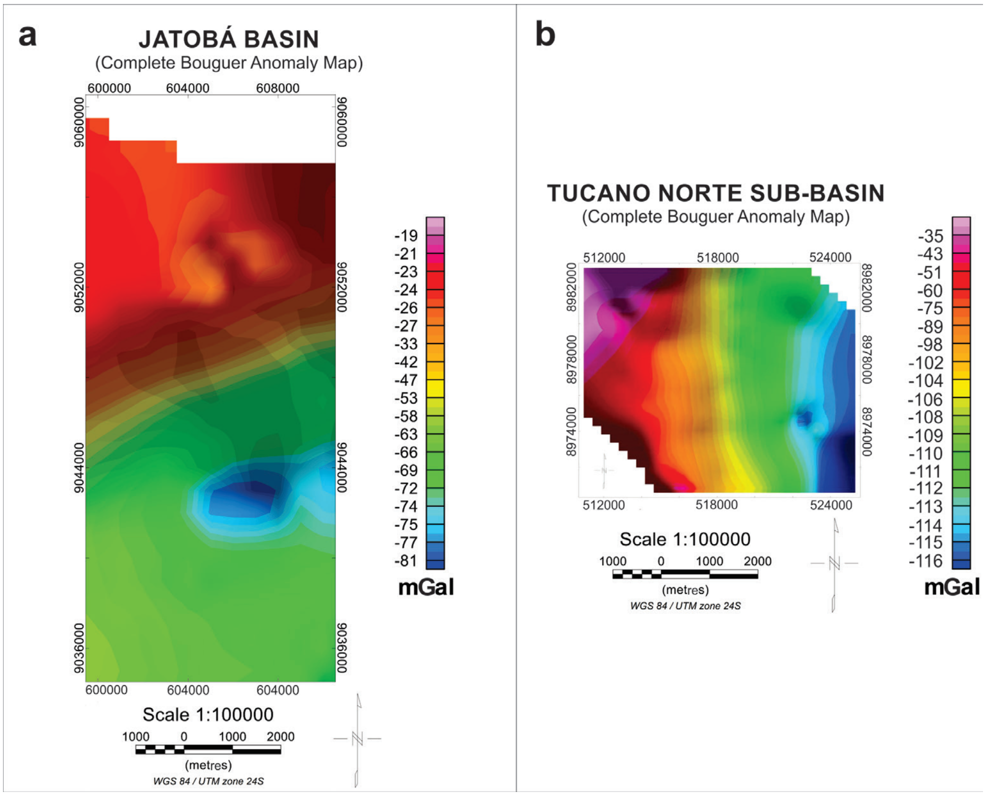

Figure 5. Bouguer gravimetric anomaly maps in the main study areas of the Jatobá Basin (a) and Tucano Norte Sub-basin (b). The data were interpolated in a 0.5 x 0.5 km grid using the least curvature method.

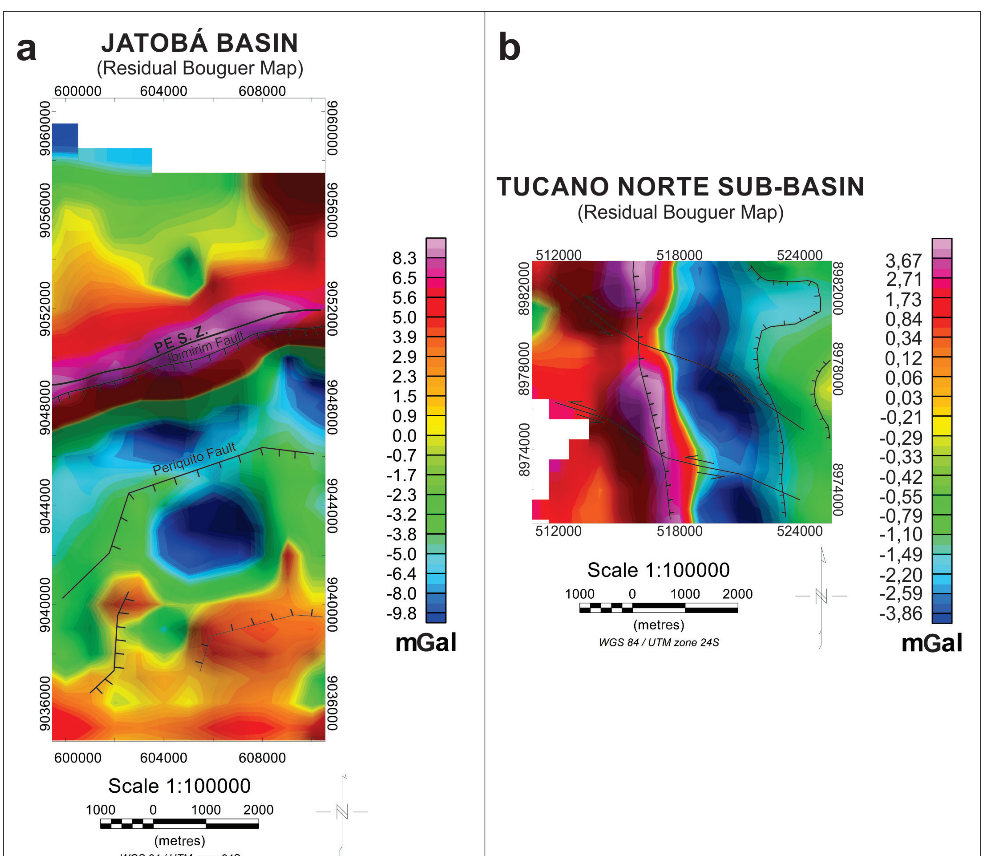

Figure 6. Bouguer residual anomaly map of the study area in the Jatobá Basin (a) and Tucano Norte Sub-basin (b). The continuous lines represent shear zones, and the lines with the small transverse lines represent faults and their dip directions.

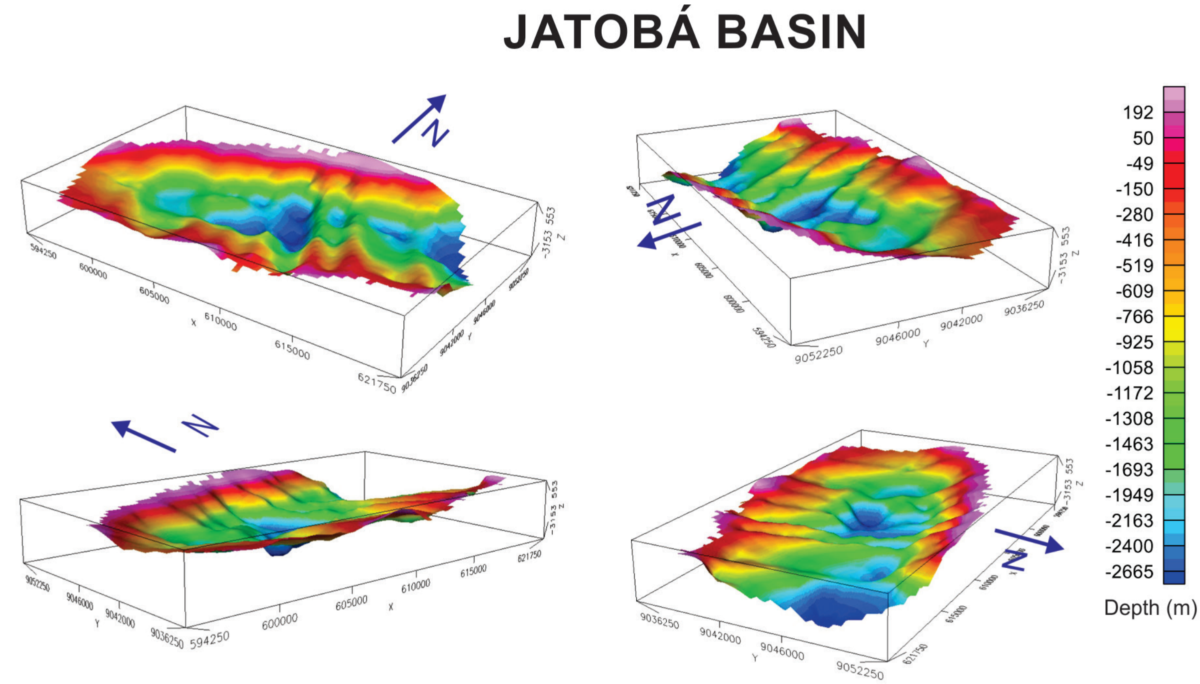

Figure 7. **Three-dimensional framework of the Jatobá Basin study area. The model indicates that the basin is semi-graben-shaped, contains small horsts, a faulted northwest border and deepening in the study area of approximately 2900 m.**

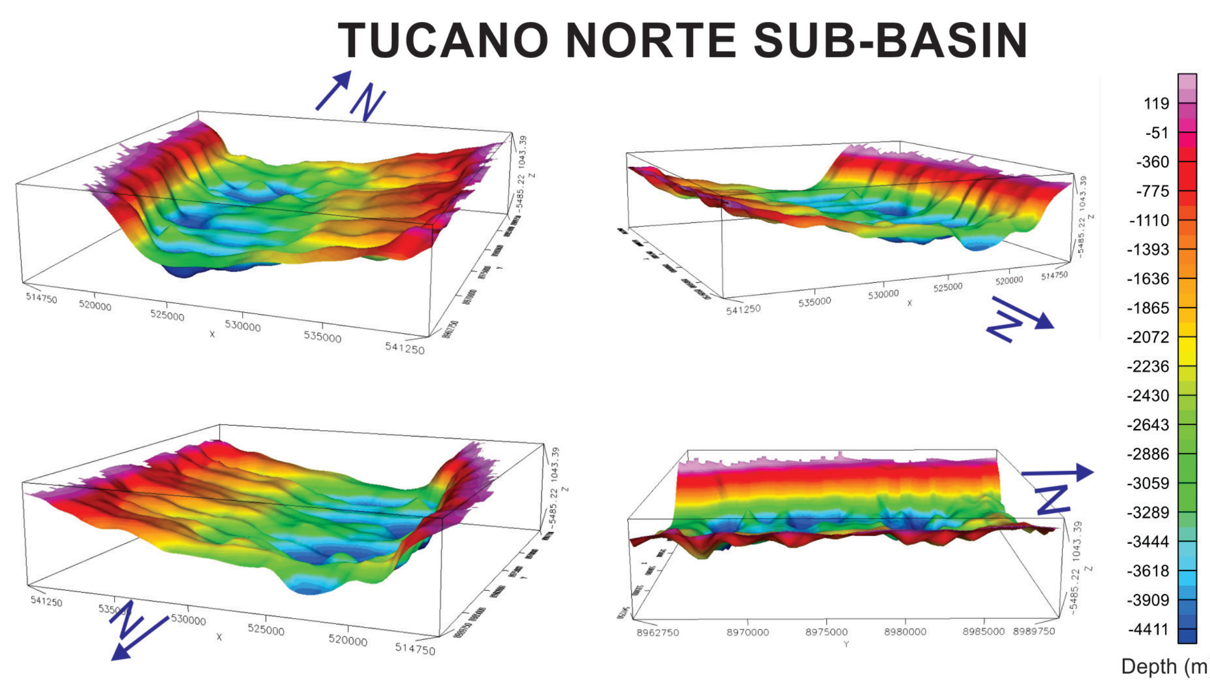

Figure 8. **Three-dimensional framework of the Tucano Norte Sub-basin study area. The model indicates, similar to the Jatobá Basin, the presence of small horsts and a general semi-graben shape, but with a failed edge to the west and tailings in the study area of approximately 5100 metres.**

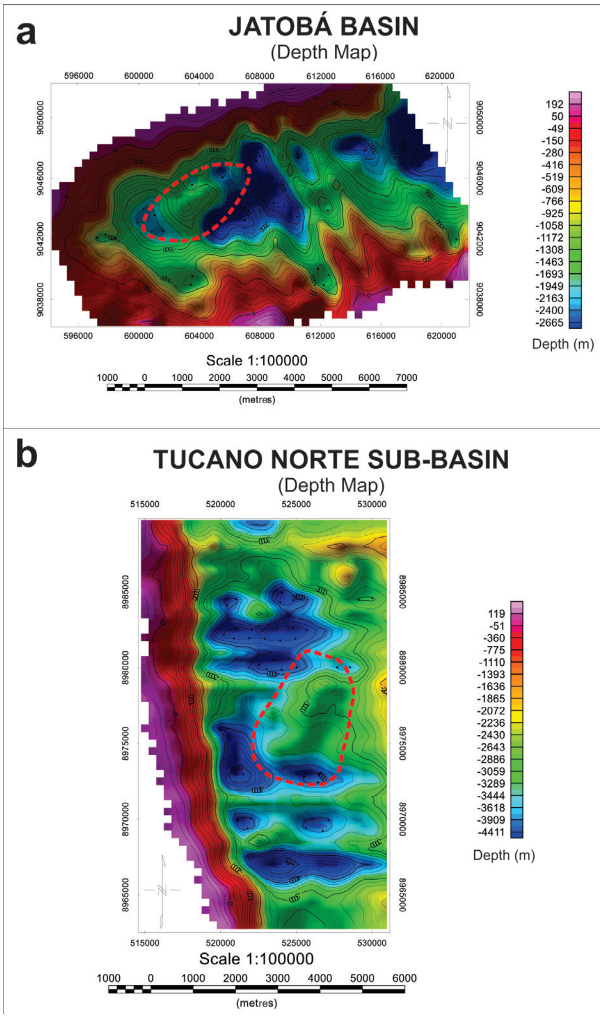

Figure 9. Framework of the crystalline basement in the Jatobá Basin (a) and Tucano Norte Sub-basin (b) calculated with 2D modelling. The dashed areas in red represent horsts of the basement that are under Aptian sedimentary rocks.

DISCUSSIONS

Magnavita (1992) studied the Recôncavo-Tucano-Jatobá Rift Basin (SBRTJ) and observed the main structural elements: (a) Edge fault; (b) Flexural margin; (c) Steps; (d) Low antithetical and Synthetic structure; (e) Platform; (f) Accommodation area; (g) Low; and (h) Structures in unconsolidated sediments (growth fault, shale diaper, fold at the end of the failure and differential compaction (Figure 10).

The results obtained in this work are compared with those of Magnavita (1992); However, the area of this study is much smaller than that in Magnavita (1992), there are similarities in the structures, such as edge faults (São Saité and Ibimirim) and internal faults, grabens, structural lows (Salgado do Melão and Ibimirim) and horsts.

Sections 1 and 2 (Figure 10) show that the grabens in the Tucano Norte Sub-basin and Jatobá Basin have semi-graben shapes, with the deepest parts in the vicinity of the edge faults.

When observing the Bouguer anomaly gravimetric maps (Figure 5), only one depocentre is highlighted in each study area (the Tucano Norte Sub-basin and Jatobá Basin).

The map of gravimetric anomalies presented by Magnavita (1992) also presents a single depocentre for both the Tucano Norte Sub-basin and the Jatobá Basin (Figure 11).

In the Bouguer residual anomaly maps (Figure 6), grabens, horsts and internal faults are visible.

The maps of the basement framework calculated by 2D modelling show grabens with more elongated shapes perpendicular to the edge faults in both the Tucano Norte Sub-basin and the Jatobá Basin (Figures 8 and 9).

Silva (2013) studied the dynamic evolution of the Recôncavo-Tucano-Jatobá Rift Basin system from field data. Silva (2013) noted that the basement had a decisive influence on the construction of the rift. In addition, pre-existing ductile structures played an important role in the construction of the rift's structural framework and its fractal character, and the regional tectonic divisions influenced the dynamic evolution by channelling tensions and shaping the regional geometry of the Recôncavo-Tucano-Jatobá Rift.

The data of Silva (2013) for both the Tucano Norte Sub-basin and the Jatobá Basin are consistent with the results in this study: the basement with elongated grabens

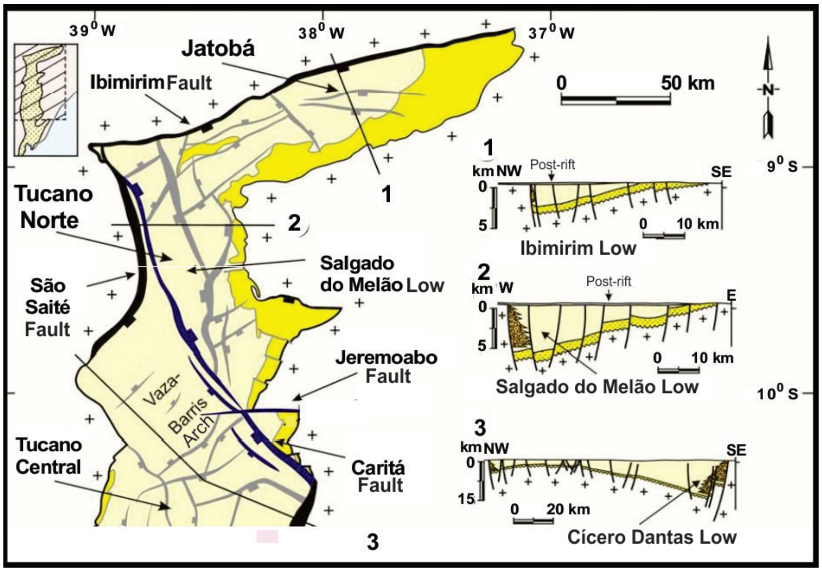

Figure 10. Simplified tectonic map of part of the Tucano Central Sub-basin, Tucano Norte Sub-basin and Jatobá Basin (modified from Aragão & Peraro 1994); sections 1, 2 and 3 are also shown (Magnavita 1992).

perpendicular to the edge fault influenced Aptian sedimentation in the post-rift I phase.

Assine et al. (2014) observed that the post-rift I sequence in the Tucano Norte Sub-basin consists only of the Marizal and Crato Formations. In the Jatobá Basin, the post-rift I sequence is composed of the Marizal, Crato, and Romualdo Formations. Why is there no Romualdo Formation in the Tucano Norte Sub-basin: erosion or a lack of deposition? In this context, what is the influence of tectonics, as revealed by gravimetry data?

The structural evidence revealed by the gravimetric models indicates that part of the relief where both the Negra and Tonã Hills are found was generated by the partial uplift of blocks of the crystalline basement during possible reactivation. Therefore, this event would have occurred later than the deposition of sediments from the Aptian formations.

Although gravimetry points to a greater depocenter depth in the Tucano Norte Sub-basin, there is no Romualdo Formation in complementing the Aptian sequence within this sub-basin creates a great unknown in the history of its formation. Thus, it is still not possible to state with certainty the reason for the absence of the Romualdo Formation in the Tonã Hill, and it is only possible to raise hypotheses, such as the following:

1- There was no deposition of Aptian sediments in the Romualdo Formation in the Tucano Norte Sub-basin.

2- There was deposition; however, the Romualdo Formation was completely eroded in the Tucano Norte Sub-basin.

3- Taking into account the proximity between the basins and the sedimentological and structural similarities, there was a connection between the two Aptian paleolakes.

The data obtained in this work and from other works presented in the discussions, it is suggested that the Romualdo Formation was deposited in Serra do Tonã, but it was eroded.

CONCLUSIONS

In conclusion, through the three-dimensional model built, this work revealed a new perspective of the Jatobá Basin and Tucano Norte Sub-basin under the Aptian paleolakes, providing an understanding of the constitution of the current relief and part of the disposal of its sediments.

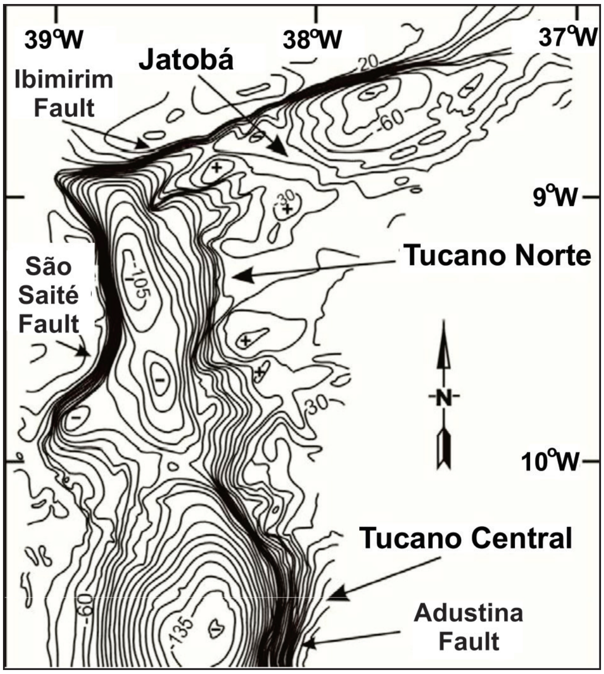

Figure 11. Map of gravimetric anomalies in the Tucano Norte Sub-basin and Jatobá Basin (modified from Magnavita 1992), showing the depocentres of the sub-basin and basin. The contour lines are in mGal.

The Bouguer residual gravimetric anomaly map generated more detail, showing the presence of several grabens in the Tucano Norte Sub-basin and in the Jatobá Basin.

The depth map, which shows the framework of the crystalline basement and thickness of the sediments in the Jatobá Basin and Tucano Norte Sub-basin calculated using 2D modelling, allowed us to visualize that the grabens are elongated perpendicular to the edge faults.

The data from this work can be used as a basis for future studies of the basins involved in this study and for future studies of related basins.

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Function of each participant of the manuscript: author Rafael Lima participated in the entire manuscript process, from the first draft to the final stage, improving and making corrections, from the research stage to the obtained results. Author Roberto Oliveira prepared the figures and table. The author Paulo Correia made suggestions and contributed to the geological setting. Author Alex Moraes revised and improved the results and discussions of the manuscript. The author Virgínio Neumann provided guidance, revised and made suggestions for the entire manuscript.