Architecture of northeast edge of Parnaíba basin, based on geophysical data.

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Abstract

An integrated study of geophysical data was undertaken in the northeast edge of Parnaíba Basin, NW Ceará. Qualitative and quantitative interpretations of geophysical data were performed in order to understanding tectonostratigraphy relationships involving the northeast part of Parnaíba Basin based on main geophysical lineaments, geometry and depth of sources. The results show structural lineaments partitioning characterized by lineaments in the 1st NE-SW order direction and 2nd EW and NW-SE order directions. The magnetic and gravity profiles of the northeast edge of Parnaíba basin estimated sources up to 5 km depth. The 2D magnetotelluric inversion shows that the northeast edge of the Parnaíba Basin is marked by low and high resistivity values, and maximum thickness of the sedimentary package reaches approximately 3 km. Subvertical dipping resistive anomalies point features that can represent Brasiliano shear zones which seem to limit the graben features that occur in the region. Such features may indicate areas with greater chances of success in the exploitation of groundwater.

Introduction

The Parnaíba Basin is a large Paleozoic syneclise in northeastern Brazil underlain by Precambrian crystalline basemente which comprises a complex lithostructural and tectonic framework formed during the Neoproterozoic-Eopaleozoic Brasiliano-Pan African orogenic collage.

Góes and Feijó (1994) described the Parnaiba basin as occupying over 600,000 km² and comprising up to ~3.4 of Phanerozoic sedimentary section overlying localized rifts.

The region where is inserted the study area have geophysical anomalies as three gravimetric lows with NE-SW orientation. These anomalies are correlated with basement structures inferred by previous geophysical data (Castro *et al*., 2014).

Regional Geological Context

The Parnaíba Basin is a large cratonic Paleozoic-Mesozoic basin in central and northeast Brasil, which caps these Cambrian-Ordovician grabens and vast areas of the Precambrian basement (Cordani *et al*., 1984). The main stratigraphic units in the study area and adjacencies are, from age: 1) the Paleoproterozoic basement represented by gneisses and migmatites of Granja Complex; 2) Neoproterozoic basement characterized by rocks of Martinópole Group, Ubajara Group, and post-orogenic granite known as Mucambo; 3) Paleozoic sediments of Jaibaras Rift and; 4) Cenozoic Sediments of Parnaiba Basin as Serra Grande Group characterized by sandstones and conglomerates (Figure 1). The profile of study area crosses important lineaments or shear zones which apparently are not exposed in this region: Café-Ipueiras Fault (CIF) and Sobral Pedro II lineament (Transbrasiliano) (SZSPII). These two lineaments limite Jaibaras basin which occurs next northeast boundary of basin. Besides, the Transbrasiliano divide two distinct tectonic domains in setentrional portion of Borborema Province, Ceará Central Domain and Médio Coreaú Domain (Figure 1).

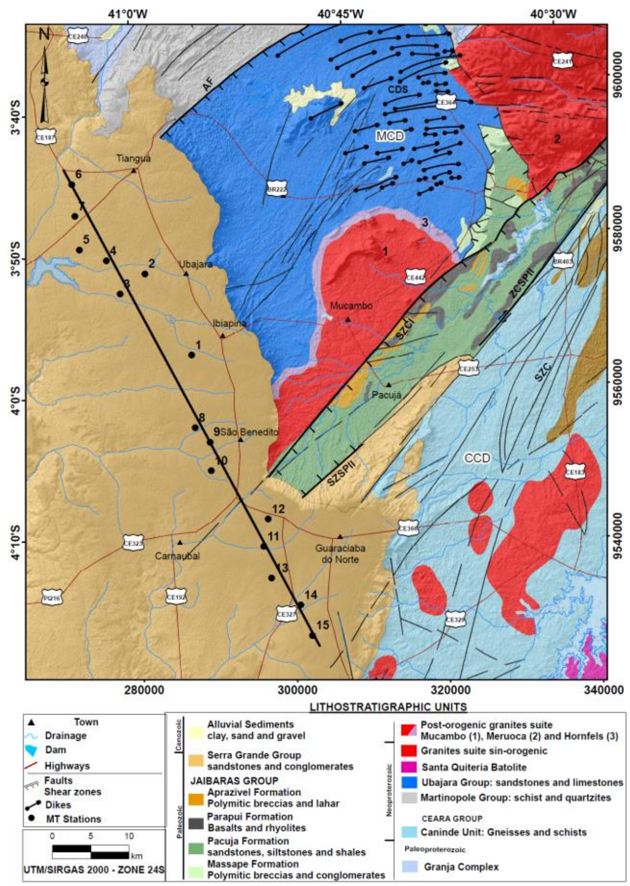

Figure 1: Geological map highlighting the main lithostratigraphic units and structures in the study area. MCD: Médio Coreaú Domain; CCD: Ceará Central Domain; SZSPII: Sobral-Pedro II Shear Zone; CIF: Café-ipueiras Faul; SZC: Cariré Shear Zone; AF: Arapá Fault; CADS: Coreaú-Aroeiras Dike Swarm. Note the profile of

geophysical data in black. (Modified from Cavalcante et al., 2003; Santos et al., 2002, 2008).

Geophysical Datasets

Airborne magnetic data

Two aeromagnetic data were merged in this study, the Rio Acaraú project and Bacia do Maranhão project (east block). These magnetic survey were derived from the Brazilian Geological Survey (CPRM) data bank and were collected in 1975 and 1988 with different flight elevations (150m to 1000m), direction N-S and spacing between lines (1000m and 3000m), respectively (Figure 2).

These aeromagnetic data were corrected for diurnal and main component of the geomagnetic field variations IGRF (International Geomagnetic Reference Field). These data were then interpolated into 250m and 750m regular grid by the bi-directional method in order to generate the anomalous field. After this procedure, several filtering techniques were applied to improve the signal/noise relationship and to highlight specific features of the magnetic sources.

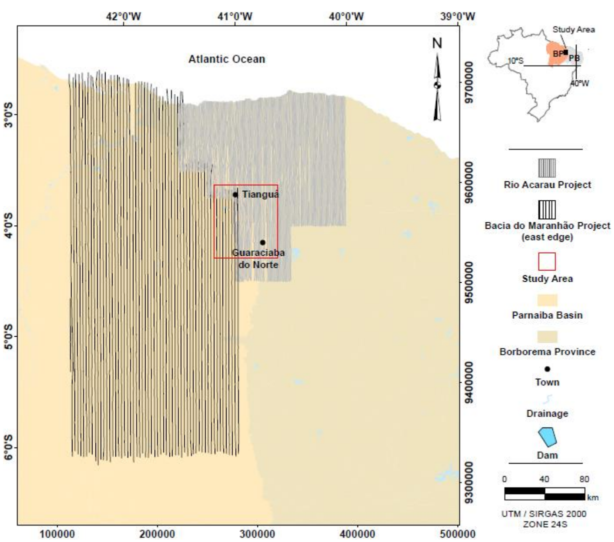

Figure 2: Aeromagnetic projects location map used in the research.

Gravity data

The study site has low density terrestrial gravity coverage, concentrated along major highways, acquired by universities and public agencies in Brazil. In addition to these data 500 new gravity stations were acquired using SCINTREX digital gravimeter model CG-5, only part of these stations were used for this study. The Figure 3 shows the distribution of previous gravity stations (49) and the newly acquired stations (101), with spacing between stations from 5 km. The gravity data were interpoled by the kriging method, in 1250 m square cell.

Magnetotelluric data

The magnetotelluric data was acquired to support 2D gravity modeling and reduce ambiguity by increasing the number of physical parameters observed in region. 15 stations were acquired along an approximate 70 km long profile spaced at 4 km (Figure 1). The model with the resistivity distribution in the subsurface in the northeast portion of the Parnaiba basin (Figure 8) was generated from the Ocamm inversion algorithm with 2D performance (de Groot-Hedlin and Constable, 1990). The joint inversion procedure for magnetotelluric data was performed with the TE modes (transverse electric) and TM (transverse magnetic) by softness link.

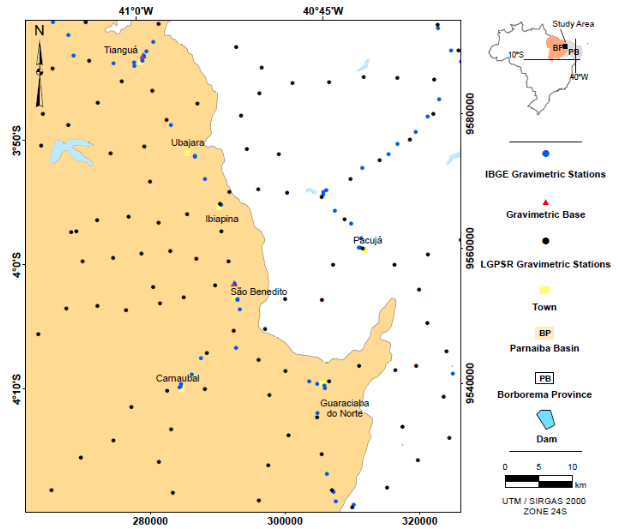

Figure 3: Map of the study area with the distribution of gravimetric stations.

Results

Magnetic data analysis

3D Euler deconvolution was performed for semi-quantitative interpretation and estimation of magnetometric residual sources (Thompson, 1982; Reid *et al*., 1990). All indices were applied so that each source was better defined, however, index 3 was the one that best homogenized with the area. Since it is necessary understand the depth of the contacts and structures, using a 10000 m spatial window and 10% maximum depth tolerance.

The spatial window and maximum depth tolerance parameters were chosen iteratively, by analyzing the results obtained when the parameters changed. Choosing of parameters was based on the number and distribution of Euler solutions as well as on maximum and minimum values, average and standard deviation, in order to obtain representative data and avoid discrepancies.

The Figure 4 shows a higher concentration of Euler solutions in the range from 2000 m to 4000 m depth. The study area has expressive solutions aligned along NE-SW probably associated with Café-Ipueiras fault and Transbrasiliano lineament. In the southeast, next Carnaubal city, the Euler solutions have a depth of 6.000 m aligned along NE-SW. This feature can be related to an extension of Café-Ipueiras fault. In Tianguá region, appear solutions clouds with 8.000 m deep and aligned along NE-SW and may be associated with Arapá fault that is not exposed in region, however it is charted in Médio Coreaú Domain, Borborema Province (Figure 1).

Gravimetric data analysis

3D Euler deconvolution was performed for semi-quantitative interpretation and estimation of gravity residual sources (Thompson, 1982; Reid *et al*., 1990). The index 0 was chosen due its relationship with linear and features, since it is necessary understand the depth of the contacts and structures, using a 12500 m spatial window and 15% maximum depth tolerance.

The figure 5 shows a higher concentration of Euler solutions in the range from 4000 m to 6000 m depth. Along to Transbrasiliano lineament most gravimetric sources are concentrated over 6000 m of depth, with shallow sources perceived outside of basin context. Concentration of deep solutions (over 8000 m) appears mainly in the south of study area, between Carnaubal and Guaraciaba do Norte cities. It is possible to note two lineaments very expressive aligned along NE-SW next the Ibiapina and Ubajara cities.

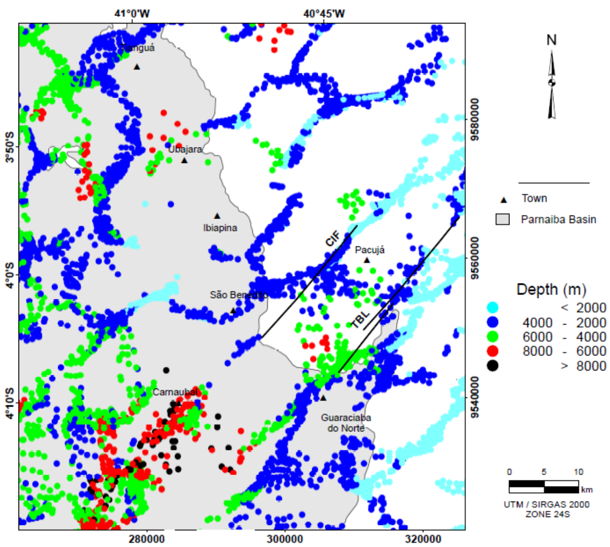

Figure 4: 3D Euler Deconvolution using structural index 3 (magnetic sources).

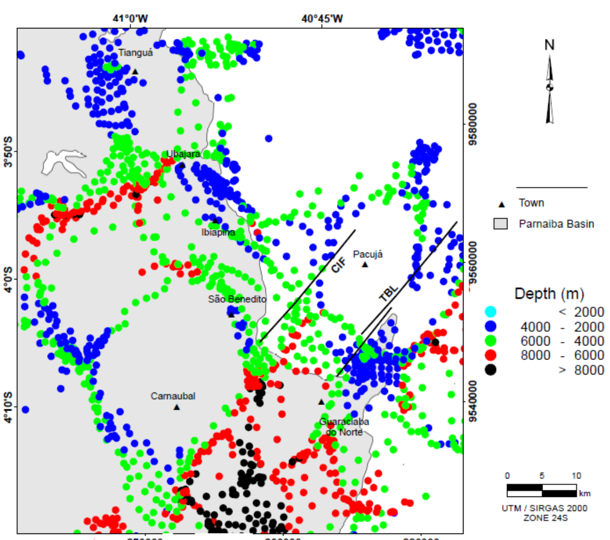

Figure 5: 3D Euler Deconvolution using structural index 0 (gravimetric sources).

2D gravity forward modeling

An NW-SE trending, approximately 70-km long profile, transverse to the Transbrasiliano lineament, was determined in the study area to analyze the 2D magnetic and gravity sources, as well as 2D gravity modeling (profile in Figure 1), and magnetotelluric response (Figure 8). The initial model was created based on potential methods, previous researches (Castro *et al*., 2014; Pedrosa Jr, 2015) surface geology data and 3D and 2D Euler deconvolution (Figure 7). The densities were established based on existing literature to the main litostratigraphic units present in the area (Telford *et al*., 1998; Castro *et al*., 2014; Pedrosa Jr, 2015). The fit between observed and calculated curves for the model is 0.149. It has been inserted a number of blocks compatible with regional geology in region (Figure 1).

In general, was adopted the average density of 2400 kg/m³ for Group Serra Grande rocks. Martinopole Group schists and quartzites are about 2720 kg/m³, while Group Ubajara limestones are 2620 kg/m³. Moreover, the average density of Mucambo Granite is about 2680 kg/m³, while rocks of the Pacujá Formation have average densities of 2670 kg/m³. The average densities of Canindé unit are about 2750 kg/m³. It was inserted a basement block in the upper crust, just below the supracrustal rocks of Médio Coreaú Domains, with density of 2750 kg/m³.

In profile NW-SE (Figure 6), with regard to depth estimates in model, there was no contribution of registered wells because there are no wells with depths greater than 300 m. In addition, there is no information about possible depths values of the basement of the east edge of Parnaíba Basin. Thus, the information about the basement depth obtained in modeling comes only from the densities of the rocks of the region existing in the literatures and the 3D Euler deconvolution (Figure 5). The thickness of the rocks along this section can reach 3000 m. In general, the gravimetric anomaly present in this section ranges from 3.5 to -9.2 mGal, where the two gravimetric lows reach -9.2 mGal and -6 mGal. The two gravimetric minima, positioned at 10 and 63 km, are called the low-gravity Tianguá and the lower gravimetric Guaraciaba do Norte, respectively. In terms of groundwater resources, this is a good indication for the Serra Grande aquifer system.

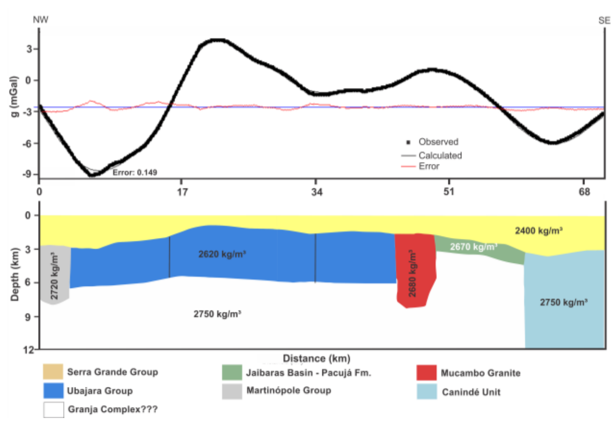

Figure 6: 2D gravimetric modeling with the adopted densities and observed residual gravimetric data.

Figure 7 shows magnetic and gravity anomalies and Euler solutions for the magnetic and gravity data using structural index from 0 to 1. The whole profile has deep solutions (5000 m), which justifies the strong influence of these structural discontinuities in the development of the Parnaíba Basin. The extension of the Sobral Pedro II Shear Zone (SZSPII) or Transbrasilian lineament (TBL) and the Café-Ipueiras Fault (CIF) (Figure 1), which were characterized on the surface, are well pronounced by solutions clouds and reach depth up to 5000 m and 3000 m, respectively. At approximately 2 km, 22 km and 35 km from the beginning of the profile other lineaments are interpreted. These exhibit characteristics similar to LTB, with clouds of solutions of 5000 m of depth and subvertical dip. These features will be denominated, in an interpretative way, of Arapá Fault (FA), Ubajara Fault (UF) and Ibiapina Fault (IF), respectively.

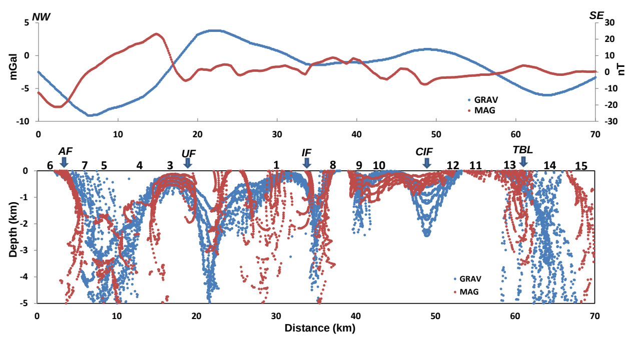

Figure 7: Magnetic and gravimetric profile at the top and Euler solutions at the bottom. AF: Arapá Fault; UF: Ubajara Fault; IB: Ibiapina Fault; CIF: Café-Ipueiras Fault; TBL: Transbrasiliano Lineament.

Magnetotelluric data analysis

The final model resulting from the simultaneous inversion of TE and TM mode present the Graben G1 which shows structure subdivided by Arapá and Ubajara faults (FA and FU), with a depth up to 3000 m (Figure 8). A strong conductor is evidenced approximately between 3000 and 6000 m of depth, having a width of the order of 5 km. Its existence, at first, would support interpretations based on lateral variations of density in the crust associated with the Ubajara Group. The resistive portion that appears in the upper left inversion of the figure is due to a poor fit for the high frequencies of station 4. The inversion artifact (IA) persisted in the simultaneous final inversion model because it is an adjustment of the two modes (TE and TM). However, there is no other geophysical evidence in this work that proves such a feature.

Graben G2 appears slightly different from its equal in TE mode. This is because the Café-Ipueiras and Transbrasiliano lineaments exert a strong influence on their compartmentalization and, perhaps, depth. Its most conductive portion reaches the depth of 3200 m. The two grabens are embedded in a basement with values of resistivities greater than 1500 Ω.m. The shallower portions of the basin are in depth around 2000 m with values up to 300 Ω.m, except for the portion influenced by the high resistivity value of the Mucambo granite. Thus, we can estimate that the geoeletric base, in áreas where it is not influenced by the compartmentalization of the grabens, is the depth of 1500 to 2000 m.

The most conductive regions in the grabens may be associated with the pelitic facies of the Jaicós Formation. Another explanation would be in the presence of water with large amounts of salts in these layers. It is worth mentioning the strong influence of the structural discontinuities (faults) in the compartimentalization of the grabens and basement in the northeast edge of the Parnaíba Basin.

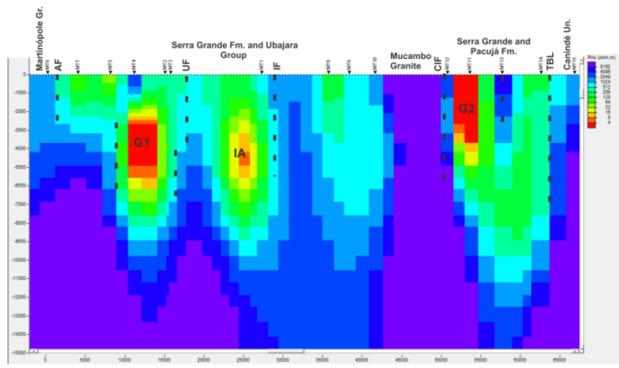

Figure 8: Electrical resistivity model resulting from the simultaneous 2D inversion (TE and TM mode). AF: Arapá Fault; UF: Ubajara Fault; IB: Ibiapina Fault; CIF: Café-Ipueiras Fault; TBL: Transbrasiliano Lineament.

Geological Model

From the gravimetric model (Figure 6), interpretations of magnetometric data, source estimates from the 2D and 3D Euler deconvolutions, and the TE and TM 2D inversions, the geological model was generated for the profile (Figure 9). This model shows the geometry of the northeastern edge of the Parnaíba Basin, which crystalline basement is very heterogeneous. The contacts between the supracrustal and basement rock sequences occur through discontinuities or lineaments interpreted in the estimations of magnetic and gravimetric sources, as well as in the gravimetric model and MT inversions. Two grabenform structures are identified in the NW and SE portions of the profile, being limited by the Arapá and Ubajara faults, and the Café-Ipueiras and Transbrasiliano lineaments, respectively. The model also shows that the SE graben of the profile is deeper and has more lateral discontinuities, which are extend even to the sediments of the Serra Grande Group.

This entire crustal segment is marked by important structural discontinuities, which were responsible for structuring the grabens contained in the study area. The Ubajara and Ibiapina faults cut from the metasedimentary rocks of Ubajara Group to the base os Médio Coreaú Domain (MCD). The Mucambo Granite appears embedded between the metassedimentary rocks of the Ubajara Group, the Jaibaras Group and the basement of the MCD. In the SE profile is possible to note a greater influence of the Café-Ipueiras and Transbrasiliano lineaments in the structural framework of the NE of the Parnaíba Basin, where reactivations during the Phanerozoic, mainly of the LTB, are responsible for the current structural of the NE edge of the basin.

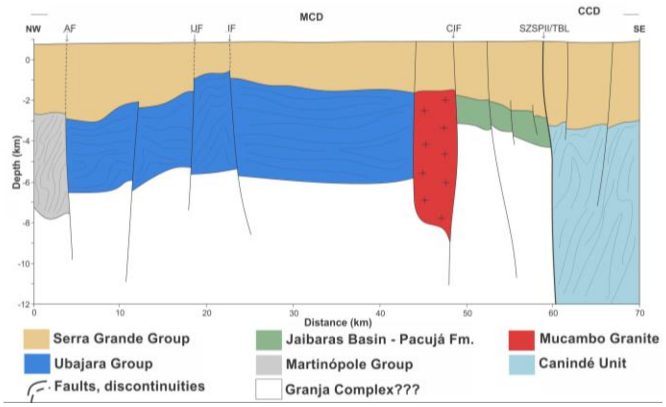

Figure 9: Geological model of NE edge of Parnaíba Basin. MCD: Médio Coreaú Domain; CCD: Ceará Central Domai; AF: Arapá Fault; UF: Ubajara Fault; IB: Ibiapina Fault; CIF: Café-Ipueiras Fault; TBL: Transbrasiliano Lineament.

Conclusions

The signature and depth of the magnetic and gravimetric sources were determined by the 2D and 3D Euler deconvolution and 2D gravimetric modeling. Several subsurface discontinuities/faults were interpreted and mapped, some of which are exposed in the Borborema Province, such as the AF, CIF and LTB. The discontinuities/faults of Ibiapina and Ubajara, which are not well marked on the surface, appear very pronounced in subsurface in the various maps and geophysical models. They present similar characteristics to the CIF and LTB, with 2D Euler clouds solutions reaching depths greater than 5000 m and with subvertical dip.

The spatial arrangement of the two grabens indicated by the geophysical anomalies is related to the lineaments that occur in the region. The graben in the NW portion of the profile is limited by the Arapá and ibiapina discontinuities/faults, while the graben of the SE portion of the profile is associated with the CIF and LTB. 2D gravimetric modeling was established from the creation of blocks with different densities, which show the configuration of the structural framework of the NE edge of the Parnaíba Basin as a set of asymmetric grabens and horsts. The model was based on 3D Euler deconvolution data, density data and previous work, involving the interpretation and modeling of gravimetric data. The result of the 2D modeling of the gravimetric data showed an error of approximately 0.15%.

The magnetotelluric section allowed a deeper investigation, with determination of the discontinuities associated to resistivity variations of the detected geological units up to 15 km deep (upper crust). The northeast region of the Parnaíba Basin is marked by complex internal structure, with sequences of grabens and horsts, in addition to expressive volume of sedimentary and metasedimetary rocks in subsurface. The sedimentary package has a variable thickness, between 1000 and 3200 m. This result is corroborated by geophysical studies using the MT method (Metelo, 1999) at the southeast edge of the basin, where maximum values of the order of 3000 m were obtained for the basement depth in São Raimundo Nonato and São Joao do Piauí cities.

The integrated magnetometry, gravimetry and magnetotelluric work provide unprecedented information of the nature of the subsurface to the NE edge of the basin, indicating areas with a greater probability of success in the exploitation of groundwater, contributing in a relevant way to future hydrogeological works.

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