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Insights on the framework of the Carajás Province, Amazonian Craton, Brazil, and on the three-dimensional shape of the Carajás Basin, based on gravity data

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Abstract

This work interprets and models aerogravity data surveyed in the Carajás Province (also Carajás Domain) - Eastern Amazonian Craton, with the purpose of understanding the deep tectonic framework of this region and sketching the three-dimensional shape of the Carajás Basin. Initially, a comparison was made between the gravity signatures of the Carajás Domain in relation to those of the Rio Maria, Bacajá and Iriri-Xingu domains. This comparison demonstrates that the gravity anomaly configuration of the Rio Maria Domain is similar to the tectonic pattern observed in ancient Archean terranes (dome-and-keel geometry) elsewhere, while the gravity anomaly arrangement of the Carajás Domain forms positive gravity belts suggesting the deposition of volcano--sedimentary rocks in elongated basins. The gravity pattern observed at the boundary between the Carajás and Bacajá domains has similarities with the shape observed in continental collision belts from several continents. The Iriri-Xingu Domain, unlike the other three domains, presents an expressive negative gravity signature. In the Carajás Basin, I observed a strong correlation between positive gravity anomalies and their maximum horizontal gradient with metavolcano-sedimentary sequences. Modeling of the positive anomalies was performed using the forward method, which calculates the 2.5D geometry of bodies associated with the anomalies. The results demonstrate that N-S intrabasinal highs divide the basin into three distinct compartments: East, Central, and West. Internally, these compartments are structured in down-dropped and up-dropped blocks with depths ranging from 500 to 3,700 m. These results were compared to the three-dimensional geological models proposed for the Carajás Basin. This comparison suggests that the early phases of the evolution of this basin are characterized by the formation of a rift structured in grabens (down-dropped blocks) and horsts (up-dropped blocks), whose bounding faults, some of them reactivated as shear zones, facilitated and amplified the development of folds in the late phases of tectonic inversion of the basin.

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1. Introduction

The CPRM-Geological Survey of Brazil carried out an aerogravity survey in a large area in the eastern region of the Amazonian Craton, in the Pará State, Northern Brazil (Lasa Prospecções and Microsurvey 2014) (Figures 1 and 2). The gravity data demonstrated that there are differences in the signatures of the diverse tectonic domains covered by the project.

Despite the accumulation of geological knowledge over the years, the tectonic evolution of the Carajás Basin is still subject of controversy. A debate has developed regarding the understanding of the three-dimensional shape of the basin (Beiseigel et al. 1973; Araújo et al. 1988; Rosière et al. 2006) and its tectonic evolution (Pinheiro and Holdsworth 2000; Macambira 2003; Tallarico et al. 2005; Texeira et al. 2010; Tavares et al. 2018). The mapped tectonic framework resulting from the superposition of several tectonic events shows in Carajás Basin the dominance of folds and others compressive structures (e.g. Pinheiro and Holdsworth 2000; Tavares et al. 2018; Costa et al. 2016). However, the proposals for tectonic evolution do not rule out an early stage in which normal faults could have been formed along with rift development (Macambira 2003; Tallarico et al. 2005; Ferrreira Filho et al. 2007; Tavares et al. 2018). As the geological maps do not show normal faults (e.g. Costa et al. 2016), if they were formed in the initial events of basin development, these structures may have been masked or reactivated in the subsequent phases of tectonic inversion.

When considering only surface data, the geological studies have difficulties in the understanding of the three-dimensional framework of lithological units. But, access to the third dimension can be obtained through geophysical data. In addition, the geophysical investigations are facilitated when there are strong contrasts in the petrophysical properties of the rocks in the study area. Furthermore, as it is generally known, the use of gravity data in the investigation of tectonic structures is well established in the geophysical literature

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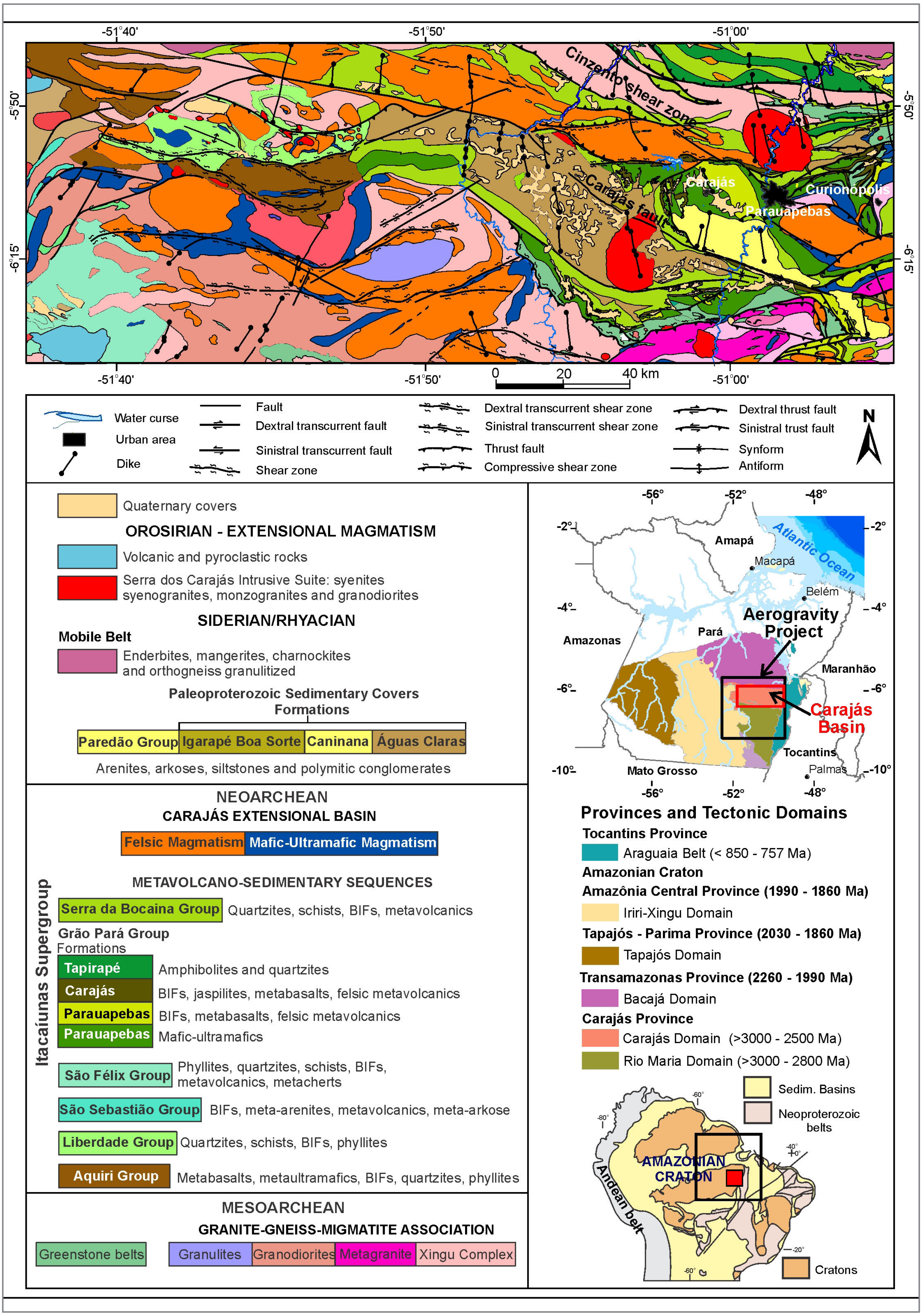

FIGURE 1.– Simplified geological map of the Carajás Basin and surroundings, Amazonian Craton, Northern Brazil, modified from Costa et al. (2016). The inset in the upper right corner shows the Amazonian Craton tectonic subdivision in the southern Pará State according to Vasquez et al. (2008).

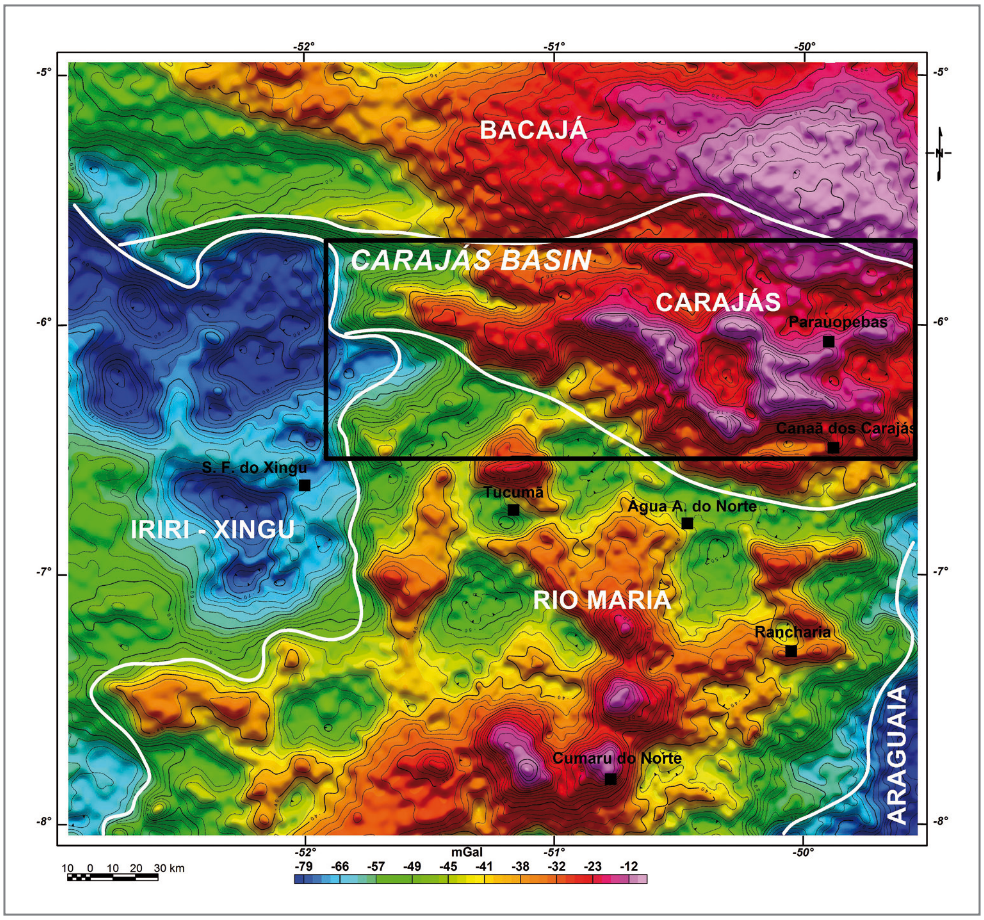

FIGURE 2 – Bouguer gravity anomalies of the “Levantamento Aerogravimétrico Carajás” project with overlapping of the boundaries of the gravity domains with designation according to the tectonic framework from Vasquez et al. (2008). The location of the Carajás Basin is indicated.

(Gibb et al. 1983; Karner and Watts 1983; Ussami and Molina 1999; Wellman 2000; Peschler et al. 2004, 2006; Silvennoinen and Kozlovskaya 2007; Gwavava and Ranganai 2009; Metelka et al. 2011).

In this work I investigated the three-dimensional shape of the Carajás Basin based on the forward modeling of gravity data and based on the premise that the three-dimensional shape of the stacking of the geological sequences can be inferred by the modeling of the positive gravity anomalies to which they are associated. The results of the gravity modeling are compared with the three-dimensional geological models proposed for the Carajás Basin. These correlations are discussed and interpretative models are proposed.

2. Geological Setting

The Carajás Basin is located in the Carajás Domain (Vasquez et al. 2008) of the Carajás Province (Santos et al. 2003) of the Amazonian Craton (Almeida et al. 1981) (Figure 1). The Carajás Province comprises the oldest nucleus of the Amazonian craton, a large continental mass generated by the fission of the supercontinent Rodinia (e.g. Li et al. 2008). The Carajás Province also includes the Rio Maria Domain in its southern region (Vasquez et al. 2008). Although they are contained in the same province, these domains show important differences; both in their lithological associations and in their geological evolutions (e.g. Vasquez and Rosa-Costa (2008) and Monteiro et al. (2014) for review of the subject and primary references). In the Carajás Domain, Archean greenstone belts and a granite-gneiss-migmatite association formed by the Xingu Complex (tonalite gneisses to trondhjemite and migmatites), granodiorites, metagranites, as well as the Pium Complex composed of mafic and felsic granulites make up most of the Archean basement. Around 2.87 to 2.83 Ga, these rocks assemblages were intruded by calc-alkaline to alkaline granitoids (Machado et al. 1991; Barros et al. 2009; Feio 2011) followed by regional high-grade metamorphism and migmatization (Machado et al. 1991). In the Neoarchean, this basement was covered by metavolcano-sedimentary rocks of the Itacaíunas Supergroup (Wirth et al. 1986; DOCEGEO 1988; Machado et al. 1991), the main unit of the Carajás Basin, with the lowermost unit, the Parauapebas Formation, mostly composed of mafic rocks (DOCEGEO 1988; Vasquez and Rosa-Costa 2008). Differently from Carajás, in the Rio Maria Domain there is the predominance of Mesoarchean greenstone belts surrounded by coeval magmatism comprising TTG associations (Macambira and Lancelot 1996; Almeida et al. 2011), sanukitoids and granites (Dall'Agnol et al. 2006; Oliveira et al. 2009). According to Tavares et al. (2018), the basement of the Carajás Domain was more affected by orogenic activities than the basement area of the Rio Maria Domain. In both domains, during the Paleoproterozoic, sedimentation and profuse anorogenic granitic magmatism took place (Machado et al. 1991; Dall'Agnoll et al. 1994;

Tallarico 2003; Dall'Agnol and Oliveira 2007). According to gravity data (Oliveira et al. 2017), in the Carajás domain the metavolcano-sedimentary sequences have positive mass (positive gravity anomalies) distribution pattern, which form linear gravity belts suggesting a deposition on elongated basins (rifts?). On the other hand, in the Rio Maria Domain, the interlacing between the positive and negative masses inside the crust, distributed in the structural style of dome-and-keel, and suggesting typical sagduction tectonics (e.g. Johnson et al. 2016) is observed. The negative masses (negative gravity anomalies) correspond to TTG intrusions that surround the metavolcano-sedimentary sequences. This mass distribution pattern is similar to that of the granite-greenstones belts of the Pilbara and Yilgarn cratons in Western Australia, and the Superior Craton in Canada (Peschler et al. 2004). The differences observed in the lithological associations, geological evolution, and gravity configuration is extended to the metallogenic context. In the Rio Maria Domain, some orogenic gold deposits are structurally controlled by shear zones (Oliveira and Leonardos 1990; Santos et al. 1998), whereas in the Carajás Domain, there are giant iron deposits (e.g. Coelho 1986; Dardene and Schobbenhaus 2001; Lobato et al. 2005; Klein and Carvalho 2008), and a large amount of world-class Iron- Oxide-Copper Gold (IOCG) deposits (e.g. Hühn and Nascimento 1997; Tallarico 2003; Grainger et al. 2008; Klein and Carvalho 2008), besides Cr-Ni-PGE (e.g. Diella et al. 1995; Ferreira Filho et al. 2007), and Au-PGE (e.g. Meireles and Silva 1988; Tallarico et al. 2000).

In this work, the interest is focused on the Carajás Basin localized in the Carajás Domain (Figures 1 e 2). According to the geological-geophysical map of project developed by CPRM-Geological Survey of Brazil (Costa et al. 2016), the Carajás Basin comprises metavolcano-sedimentary sequences of the Itacaiúnas Supergroup (Wirth et al. 1986; DOCEGEO 1988), which includes a upper sequence named Serra da Bocaina Group (dated at 2.77 - 2.73 Ga), composed of quartizites, schists, metagraywackes, metabasalts, metandesites, BIF and metavolcanic rocks. Below the Serra da Bocaina Group occurs the Grão Pará Group, dated at 2.76 - 2.74 Ga, comprising metabasalts interlayered with jaspillites, quartzites, metacherts, felsic metavolcanics, and mafic-ultramafic rocks. This group hosts one of the largest iron deposits in the world. In the western Carajás basin, Costa et al. (2016) also mapped the metavolcano-sedimentary rocks of the São Felix (phyllites, quartzites, schists, BIF, metavolcanic rocks, and metacherts), São Sebastião (BIF, meta-arenites, metavolcanic rocks, and meta-arkose), Liberdade (quartzites, schist, BIF, and phyllites) and Aquiri (metabasalts, metaultramafic rocks, BIF, quartzites, and phyllites) groups. A shallow marine Paleoproterozoic sedimentation composed of arenites, arkoses, siltstones and polymictic conglomerates partially cover the Itacaiúnas Supergroup (Águas Claras Formation, according to Araújo et al. 1988 and Nogueira et al. 1995, and the Caninana Formation of Pereira et al. 2009). In addition, Neoarchean acid magmatism, formed by alkaline to subalkaline granites with ages ranging between 2.77 and 2.72 Ga took place. These granites usually present foliations and were separated into several suites (e.g. Barros et al. 2009; Feio 2011). Furthermore, intrusions of mafic-ultramafic occurred around 2.76 Ga (Machado et al. 1991); some of them hosting Ni-PGE mineralization (Ferreira Filho et al. 2007). In the Orosirian period, there was an important event of felsic magmatism represented by alkaline to subalkaline type A granites (e.g. Macambira and Vale 1997; Dall'Agnol et al. 2005). Due to its size, the bodies of the Cigano and Central Carajás granites stand out.

In studies aiming the understanding of the three-dimensional shape of the Carajás Basin, Beiseigel et al. (1973) described a syncline with WNW-ESE axis, but Araújo et al. (1988) reinterpreted this structure as a positive flower, while Rosière et al. (2006) proposed an S-shaped synform-antiform pair with axis dipping to WNW. Pinheiro and Holdsworth (2000) described the tectonic evolution of the Carajás Basin in five phases that occurred in a long period between 2.85 and 1.8 Ga: i) sinistral transpression, ii) formation of a pull-apart basin, iii) dextral transtension and development of the Cinzento and Carajás shear zones, iv) basin inversion, and finally v) transient regime with anorogenic granitoid intrusions in the Paleoproterozoic. For Macambira (2003) and Tallarico et al. (2005) the formation of the basin occurred by the opening of an intracontinental rift. However, Texeira et al. (2010) defended the hypothesis that the volcano-sedimentary sequences of the Grão Pará Group were formed in a volcanic arc environment resulting from interactions between plate tectonics and subduction. Tavares et al. (2018) based on studies in the northeast Carajás Province describes an initial phase of extension and rifting followed by inversion of the Carajás Basin in the Neoarchean. Then, a rift phase followed by oblique reverse-dextral tectonism occurred in the Paleoproterozoic, and finally, a rift phase took place at the late Neoproterozoic/early Paleozoic boundary. Also according to Tavares et al. (2018), between the deposition of the Águas Claras Formation (2.10 - 2.07 Ga) and the Orosirian magmatism (1.93 - 1.85 Ga), the Carajás Basin was affected by two collisional events: Carajás-Bacajá (Transamazonian Orogeny, 2.07 - 2.05 Ga) and Carajás - West Africa Craton (Sereno Orogeny, 2.0 - 1.93 Ga). In addition, the region was affected by events related with the formation of the Araguaia belt (0.75 - 0.55 Ga) during the Brasiliano Orogeny, and the opening of the Atlantic Ocean in the Cretaceous (Tavares et al. 2018).

3. Data and Methods

3.1. Gravity Data

The gravity data used in this study were provided by the CPRM-Geological Survey of Brazil as part of the "Levantamento Aerogravimétrico Carajás" project (Lasa and Microsurvey 2014). This survey was carried out in an area of 50,000 km^2 located in the Pará State- Northern Brazil (Figures 1 and 2). The flight lines in the N-S direction were spaced by 3 km, while the control lines in the E-W direction were spaced by 12 km. Sampling distance along the flight lines varied between 7.65 m and 15.21 m according to the aircraft velocity used to transport the equipment. Gravity drift control readings were recorded each working day before and after the flight in a gravity base station referenced to the Brazilian Fundamental Gravity Network (Observatório Nacional). The recording was performed for 40 minutes at the aerodrome base stations. The survey was carried out at a fixed altitude of 900 m with an average speed of 275 km/h at night (Lasa and Microsurvey 2014).

Before the survey, internal gravity tests were performed with the gravimeter positioned in a gravity base station. An external consistency test was also performed on a calibration track located in Tietê (São Paulo-Brazil) (Lasa and Microsurvey 2014). In order to obtain the Bouguer and Free air anomalies, the following corrections were made: dynamic acceleration, drift, tide, eötvös and latitude (normal gravity with the 1980 formula). The Bouguer anomaly was calculated for topography with a density of 2.67 g/cm^3 (Figure 2). The final processing consisted of the leveling and micro-leveling of the Bouguer and Free- air anomaly data (Lasa and Microsurvey 2014).

3.2. Interpretation Approach

Gravity data are widely used to study the regional tectonic framework of areas of different geological evolutions (e.g. Gibb et al. 1983; Karner and Watts 1983; Ussami and Molina 1999; Peschler et al. 2004, 2006). The integrated geophysical/geological interpretation is based on evidence that the crustal framework might be associated with markedly contrasts of density between different lithology and crustal domains, as well as by gravity signatures along the structures separating these domains. The widespread use of gravity data sets in crustal studies and geological mapping is based on the fact that the characterization of lateral density variations is quite good (Silva et al. 2002a, 2002b).

One of the major difficulties in interpreting gravity data is to isolate the anomalies caused by different geological sources. So, I used the strategy of superposition of the structures and main contacts on the Bouguer anomaly map followed by the observation of the correlation between them. For this, a window was made in the main data grid that corresponds to the area of occurrence of the Carajás Basin (Figure 3A).

To model the positive Bouguer gravity anomaly associated with the metavolcano-sedimentary rocks of the Carajás Basin, the flight lines in the N-S direction that cross the study area were used. These flight lines cross the main structures and lithologies almost orthogonally (Figure 3B).

As previously mentioned, the aspects related to mass excess (positive anomalies) and deficiencies (negative anomalies) in relation to a given background are considered in the modeling of gravity data. In order to identify the positive and negative mass concentrations in the study area, a first order trend was removed in the original flight line data before the modeling. In this new grid, the values oscillate below and above zero (Figure 3B).

Horizontal gradients that represent the strongest density contrasts were calculated for the Bouguer anomaly grid (Figure 4A). The maximum of the horizontal gradients were plotted in the Bouguer anomalies with the first order trend removed (Figure 4B). The alignments of the strongest density contrasts can be interpreted as the contacts between two rock units with significantly different densities. By comparison with the geological maps, it appears that the maximum density contrasts correlate well with faults, shear zones and contacts between metavolcano-sedimentary sequences and the basement rocks.

For the modeling procedure, the forward method was adopted by means of the calculation and the comparison of the signals of 2.5D geometry bodies. Each profile, after extraction,

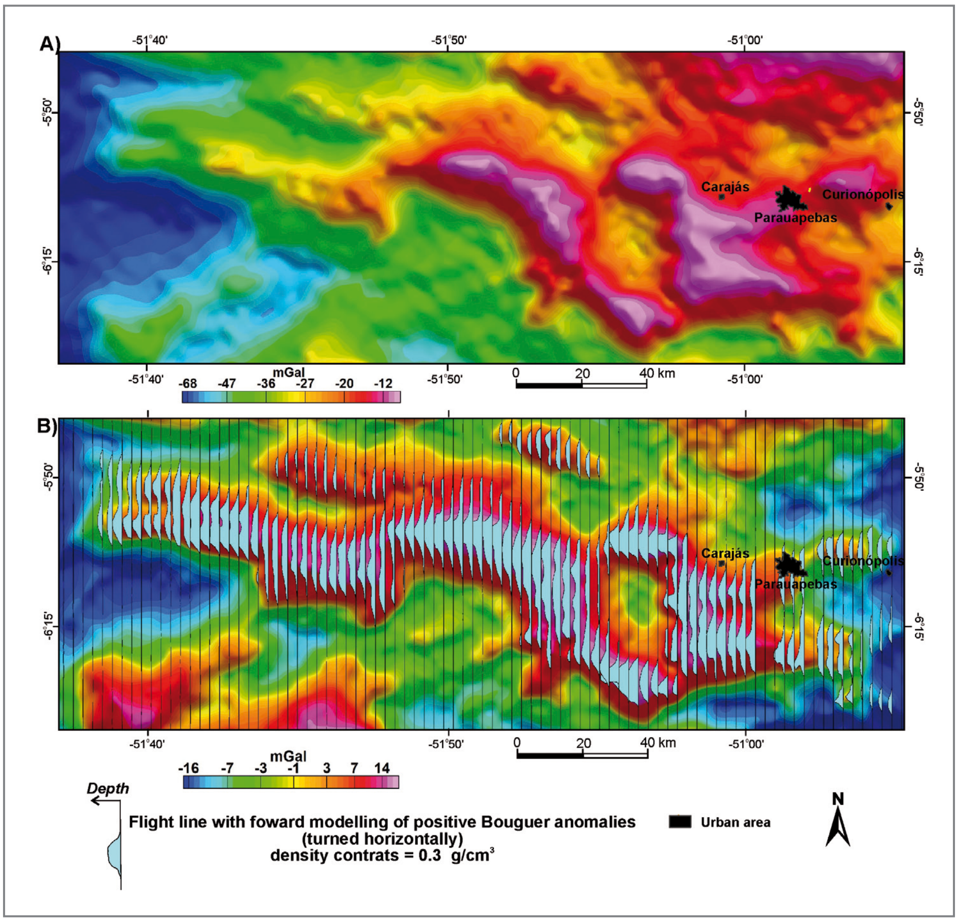

FIGURE 3 – A) Bouguer gravity anomalies of the Carajás Basin and surroundings; B) Bouguer gravity anomalies with first order trend removed, flight lines and results of the forward modeling of the positive anomalies (turned horizontally).

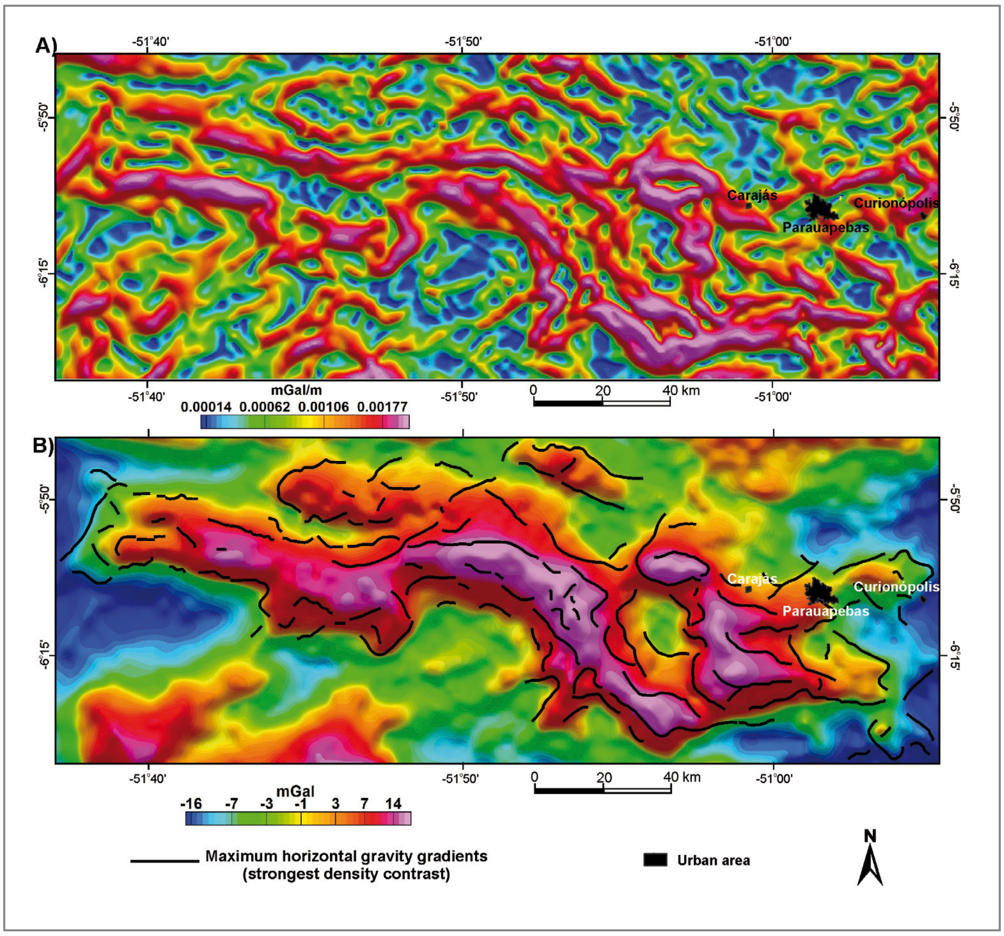

FIGURE 4 – A) Horizontal gravity gradients of the Bouguer anomalies; B) Bouguer gravity anomalies with first order trend removed and superposition of maximum horizontal gradient (black lines).

was modeled using the software Gm-sys (Geosoft). The main hypothesis for 2.5D modeling is that the gravity signature represents a basin filled by volcano-sedimentary rocks with an average density of 3.0 g/cm^3. During the modeling process, the following procedures were adopted: i) addition of blocks of high density (3.0 g/cm^3) corresponding to the mean of densities for the metavolcano-sedimentary sequences in contrast to a regional low density crust (2.7 g/cm^3); (ii) calculation of the effects; and iii) comparison of the calculated effects with the observed data. For each modeled block, known geological information was considered, such as contacts and structures. The values of the densities used in this work are compatible with values measured and used elsewhere in modeling of Archean or Proterozoic terranes (e.g. Table 1 in Peschler et al. 2004). After the modeling of each profile separately, the depth data results were compiled into a single database. Then they were interpolated for the construction of a three-dimensional model of the depth.

3.3. Limitations of the Method

The interpretation approach has some limitations, so it is important to clarify aspects related to the ambiguity associated with the interpretation of geophysical data. Although density values are well suited, the sedimentary rock package thickness can be underestimated or overestimated in situations where the ratio of more or less dense rocks undergoes large variations. Therefore, the method can lead to errors in the shape and depth of the basin. The shape of a body that fits the same gravity anomaly can vary greatly; thus, geological information is inserted to reduce ambiguity. In this study, the most appropriate geological model is that of a geological body in the shape of a basin. However, there are cases where a large volume of dense rocks occurs, such as the iron formations of the Grão Pará Group (Serra Norte and Serra Sul ridges). Since a thin, but very dense, layer can adjust the anomaly, it is possible that, in these cases, the contrast of 0.3 g/cm^3 may not be adequate, so the thickness of the basin could be overestimated. An opposite situation is also possible. Since the thickness of the Águas Claras Formation is unknown, due to the lower density of the sediments of this formation, in the places where it is very thick, the total thickness of the basin may have been underestimated.

4. Results

The integration of geophysical data with surface geological data is a complex task because of the subsurface information contained in the geophysical data. When there are no geological data from wells, it is not possible to make direct correlations. Thus, the best solution is to interpret the geophysical data using simple and coherent geological models. One of the most complicated tasks in interpreting is to separate geophysical domains that are consistent with known geological data.

4.1. Regional gravity framework

In this work, an investigation of the regional gravity data was carried out to contextualize the gravity signature associated with the rocks that fill the Carajás Basin in relation to the signatures of the adjacent geological domains. For this purpose, the separation of gravity domains was done for the whole "Levantamento Aerogravimétrico Carajás" project (Figure 2), in comparison with the five tectonic domains proposed in the geological map of the Pará State (Vasquez et al. 2008): Rio Maria, Carajás, Bacajá, Iriri-Xingu and Araguaia.

The Rio Maria Domain is formed by a set of Bouguer positive anomalies with amplitudes between 15 and 25 mGal, and wavelengths between 25 and 30 km, oriented in the NNE-SSW, NW-SE and E-W directions (Figure 2). These positive anomalies surround semicircular negative anomalies with diameters between 10 and 40 km and mean amplitude of 10 mGal, which correlated with TTG orthogneiss and high-K Archean granitoids, as well as with intrusions of Orosirian intraplate felsic rocks. This gravity configuration, with absence of large-scale linear trends and interlaces between greenstone belts (positive anomalies) and TTG intrusions (negative anomalies) without a dominant direction, bears similarity to the tectonic pattern observed in ancient Archean terranes elsewhere (e.g. Windley 1995). According to Zegers and Van Keken (2010), the absence of typical plate boundary and convergence features may suggest a system of rock formation and deformation in older Archean terranes that do not include plate convergence and subduction. The boundary with the Carajás Domain is marked by a gravity linear belt with an average width of 15 km formed by negative anomalies with mean amplitudes of 10 mGal associated with intrusions of high-K Neoarchean granitoids elongated in the E-W direction.

The Carajás Domain is characterized by linear belts of Bouguer positive anomalies oriented mainly in the E-W direction with amplitudes between 10 and 30 mGal and wavelength between 20 and 30 km (Figure 2), which correlated with outcrops of metavolcano-sedimentary rocks of the Itacaíunas Supergroup. These belts surround negative anomalies associated with intrusions of Neoarchean granitoids and Paleoproterozoic covers (Águas Claras and Caninana formations), as well as of Orosirian intrusions of intraplate granites. The gravity arrangement formed by linear belts of positive anomalies with E-W direction suggests deposition of volcano-sedimentary rocks on elongated basins (rifts?).

The Bacajá Domain is characterized by Bouguer positive anomalies with mean amplitudes of 25 mGal and negative anomalies with maximum amplitudes of 14 mGal (Figure 2). The boundary with the Carajás Domain occurs through a negative gradient of 0.34 mGal/km correlated with shear zones. The gravity pattern observed at the boundary between Carajás and Bacajá domains has similarities with the pattern observed in continental collision belts from several continents (e.g. Gibb et al. 1983; Ussami and Molina 1999; Ranganai et al. 2002; Mandal et al. 2015; Spampinato et al. 2015).

The Iriri-Xingu domain, unlike the other three domains described above, presents an expressive negative gravity configuration defined by semicircular anomalies with diameters between 15 and 40 km and negative amplitudes between 15 and 25 mGal (Figure 2). The main geological correlation occurs with Paleoproterozoic volcanic rocks. Also, some anomalies have a clear correlation with Orosirian intraplate felsic intrusions. The boundary of this domain with the Rio Maria Domain is defined by a line that skirts the average boundary between the predominantly positive tendency of the Rio Maria Domain and the negative tendency of the Iriri-Xingu Domain.

The Araguaia Belt, formed during the Brasiliano orogeny, presents a small exposure in the southeast of the study area, which correlates with a negative gravimetric gradient of 0.65 mGal/km towards the belt (Figure 2). This negative gravity gradient was modeled by Ussami and Molina (1999) as the effect of the Amazonian Craton plate flexion under the weight of the nappes of the Araguaia belt.

4.2. Gravity insights on the Carajás Basin

The results of the forward modeling (Figure 5) were interpreted as the three-dimensional shape of the Carajás Basin from the superposition of the various phases of tectonic deformation that occurred throughout its evolution. I observed that the basin has truncations and intrabasinal highs in the N-S direction that divides it into three distinct compartments, here denominated East, Central and West (Figure 5). In addition, to the north of the main basin, a small down-dropped block structurally controlled by the Cinzento Shear Zone stands out.

The East Compartment corresponds to the most well-known and studied region of the Carajás Basin, where the rocks of the Grão Pará Group are dominant and the giant iron deposits of the Carajás Formation and several IOCG deposits occur. In this region, the basin is formed by two main down-dropped blocks with maximum depths of 3,700 meters, one to the north and the other to the south separated by an up-dropped block (Figure 5), which corresponds geographically and respectively to the Serra Norte (depths up to 3,700 m) and Serra Sul ridges (depths up to 1,800 m) (Figure 5). The depths of the two down-dropped blocks gradually increase to the west. The northern down-dropped block is compartmentalized in two along an N-S truncation, possibly caused by the forced intrusion of the Central granite, whose tectonic action has decreased the depth of the basin in the region (Figure 5). The south down-dropped block has a triangular shape with apex tectonically elongated to the east. In the up-dropped block that separated the two main down-dropped blocks outcrops the Paleoproterozoic sediments of the Caninana Formation. The southern border of this up-dropped block is controlled by the Carajás Fault and its top, located in the depths between 100 and 500 m, possibly constitutes the basement of the sediments of the Caninana Formation. The northern down-dropped block extends eastward from the Parauapebas town forming a trough with depths between 700 m and 1,300 m and with the southern border being controlled by the north border of the Estrela granite. The southern down-dropped block branches in small down-dropped blocks to the east (maximum depths of 1,400 meters); one of them with direction NE-SW is controlled by the south border of the Estrela granite, and the other in NW-SE direction is filled by sediments of the Caninana Formation.

The Central compartment is separated from the East compartment by the Central granite, which forms an interbasinal high between the two compartments (Figure 5). This Central compartment is formed by a single down-dropped block that has an elongated sigmoidal shape in the NW-SE direction with a total length of 110 km. To the northwest, the down-dropped block is bent in the E-W direction, possibly by influence of the Carajás Fault that controls its north border.

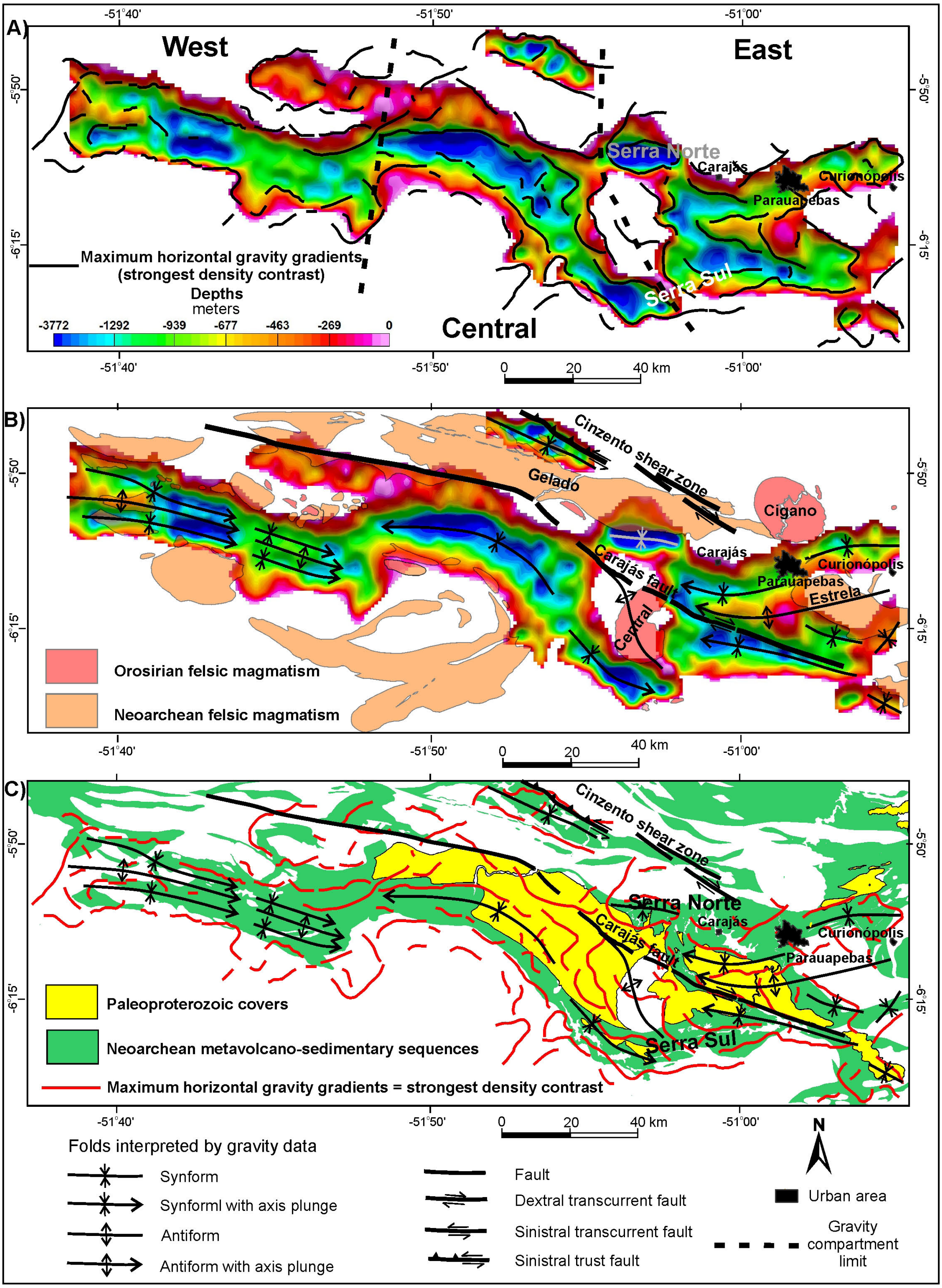

FIGURE 5 – A) Results of the forward modeling of the positive gravity anomalies correlated with metavolcano-sedimentary sequences of the Itacaíunas Supergroup with subdivision in three compartments and superposition of the maximum horizontal gradient (black lines); B) Results of the forward modeling of the positive gravity anomalies correlated with Neoarchean metavolcano-sedimentary sequences with interpreted axis of synformal and antiformal folds. The bodies of Neoarchean and Orosirian felsic magmatism are indicated; and C) Neoarchean metavolcano-sedimentary sequences and Paleoproterozoic covers with superposition of maximum horizontal gradient (red lines) and interpreted axis of synformal and antiformal folds.

To the southeast, the down-dropped block skirts the western border of Central granite and continues to its southern contact. This compartment has two depocenters: one in the northwest and another in the southeast, both with depths of 3,000 m. The two depocenters are separated by a shallower region in the central portion, with maximum depths of 1,000 m. On the surface, sediments of the Águas Claras Formation crop out, except for the southeast edge, where rocks of the São Felix Group crop out. However, the dominant positive gravity signature in this region indicates that there is a large volume of Neoarchean metavolcano-sedimentary rocks beneath the Paleoproterozoic sediments of the Águas Claras Formation.

The West Compartment is separated from the Central Compartment by a strong truncation in the N-S direction that produced sinistral relative displacement and an interbasinal high between the two compartments (Figure 5). The tectonic structures that could genetically be related to this truncation are small sinistral transcurrent faults and dikes with NNE-SSW direction (Figure 1). The truncation reduced the width and depth of the basin and limited the occurrence of sediments of the Águas Claras Formation to the west (Figure 5). This compartment, with width of 25 km and longitudinal extension of 100 km, is structured in two lateral down-dropped blocks separated by a central up-dropped block. The lateral down-dropped blocks have maximum depths of 2,500 m and the top of the central up-dropped block is in depths between 450 and 900 m. This main structure has a secondary subdivision that separates this compartment into east and west segments. This division occurred by means of N-S truncation that decreases the depth of the compartment. This secondary subdivision, interpreted by means of gravity data, has correspondence in the geological map of Costa et al. (2016) that mapped dominantly the rocks of the Aquiri Group in the east segment, and rocks of the Liberdade Group in the west segment (Figure 1). To the north of the West compartment, an axis of positive anomalies was modeled as a trough of dense rocks with a width of 10 km and an extension of 40 km. However, although in this region the Serra da Bocaina and Liberdade groups crop out (Costa et al. 2016), possibly the mass excess associated with the gravity signature is produced mainly by gneisses and granulites (Vila Sassá gneiss, Costa et al. 2016).

In the north portion of the study area, a down-dropped block with maximum depth of 900 m, controlled by the Cinzento Shear Zone, is separated from the main basin. According to the geological map of Costa et al. (2016), this down-dropped block is filled by metavolcano-sedimentary rocks of the Serra da Bocaina Group.

5. Discussions

The results of this work describe the Carajás Basin only with an alternating set of down-dropped and up-dropped tectonic blocks. This assumption, based on the premise that metavolcano-sedimentary rocks (mean density = 3.0 g/cm^3) are denser than their basement (mean density = 2.7 g/cm^3), have limitations for the identification of the geological causes that contributed to the definition of the current shape of the basin. To reduce this limitation, it is necessary to add geological information to the gravity model. In the context of the ambiguity inherent in the interpretation of gravity data, the main question posed in this article is what is the meaning of the down-dropped and up-dropped blocks? Graben and horst, or keels and domes, or synforms and antiforms folds? In the first two hypotheses, where the premise is of a dominant vertical tectonics, the gravity gradients that mark the contact of the metavolcano-sedimentary rocks with the basement would be originally normal faults. In the third case, the gravity gradients would be the result of the contact between the rocks that fill the basin and its basement without occurrences of normal faults.

Most researchers describe the history of rock deformation in the Carajás Basin as a complex evolution that includes alternating phases between extension and compression that began with the formation of the Itacaíunas Belt in the Mesoarchean (e.g. Pinheiro and Holdsworth 2000; Tavares et al. 2018). In this belt, the tectonic studies describe a ductile deformation of high temperature with well-defined records in the basement (Pinheiro and Holdsworth 1997, 2000) formed as a consequence of the collision between the Rio Maria and Carajás domains (e.g. Teixeira et al. 2010; Tavares et al. 2018). In this tectonic discontinuity, an extensional deformation system favored the formation of the Carajás Basin. Most researchers suggest that there was the development of an intracratonic rift (e.g. Macambira 2003; Tallarico et al. 2005; Tavares et al. 2018). In the work of Pinheiro and Holdsworth (2000), normal faults between blocks are only described in an extension phase after this main phase of basin deposition. Also, on the geological map of Costa et al. (2016), normal faults forming grabens and horsts within the basin were not mapped. Therefore, if there was an important development of grabens and horsts at the origin of the basin, the normal faults associated with vertical tectonics are masked by reactivation structures in the later phases of the tectonic evolution. It may also be that because of the strong weathering of the rocks, normal faults are difficult to map in the region of the Carajás Basin. Nevertheless, the Carajás Basin origin as a continental rift is suggested by several researchers (e.g. Macambira 2003; Tallarico et al. 2005; Tavares et al. 2018), including the possibility that part of the mafic-ultramafic magmatism is associated with this rift (Ferrreira Filho et al. 2007). This allows to raise the possibilities that: i) the down-dropped and up-dropped blocks modeled by gravity data (Figure 5) are grabens and horst formed in the initial phases of the basin; and ii) the maximum horizontal gravity gradient (Figure 5) demarcate the position of normal faults formed in the rift stage of the basin.

Rosière et al. (2006) suggest the possibility that originally the basin would have developed in a system of domes-and-keels. Comparing the gravity signatures of the Carajás Basin with those of the granite-greenstone terrains of the Rio Maria Domain, I observed that in the latter, the interrelationship between positive (greenstones belts) and negative anomalies (granites) in a large crustal diameter is very compatible with the structure in dome-and-keels found in Archean domains of several continents. This does not occur in the Carajás Domain, where the arrangement is formed by belts of linear positive anomalies without the presence of expressive circular negative anomalies. However, if an initial evolution has occurred in domes-and-keels, the structure as a whole would have been elongated posteriorly in the E-W direction.

Transpressional faults and folding developed in a compressive phase of the basin evolution are common structural elements in the geological map of Costa et al. (2016) and in the structural studies of Pinheiro and Holdsworth (2000). The first structural studies carried out in the Carajás Basin described a framework in the form of a faulted synclinorium with the flanks located in the Serra Norte and Serra Sul ridges (Beisiegel et al. 1973). According to Beisiegel et al. (1973), the Serra Norte ridge corresponds to the structurally more complex and less continuous flank, while the south flank (Serra Sul ridge) describes a long arc to the southwest. Reinterpreting this structural model, Araújo et al. (1988) attributed the development of folds to the dynamics of shear zones, whose movement would have produced a positive flower structure. Pinheiro and Holdsworth (2000) observed several folds, from centimeters to kilometers, associated to the transpressive movement of the Carajás Transcurrent System, whose causes were attributed to the basin inversion. Rosière et al. (2006) proposed that the structure in the region between the Serra Sul and Serra Norte ridges is a partially disrupted S-shaped synform-antiform pair with axis dipping to WNW, named the Carajas Fold. This fold system is intersected by several strike-slip faults subparallel to their axial plane.

If i consider that the basement was involved in the tectonic deformation of the basin, the synformal fold must correspond to down-dropped blocks, and antiformal fold to up-dropped blocks (Figure 5). Therefore, the results of the gravity modeling are compatible with the structural models of Rosière et al. (2006), because I observed that the Carajás Fold corresponds respectively to down-dropped and up-dropped blocks interpreted by means of the gravity data. The sense of axis plunge was interpreted as a sense of deepening of the blocks (Figures 5 and 6). If we interpret this model for the whole basin, the entire basin is structured in synformal (down-dropped block) and antiformal (up-dropped block) folds (Figure 6). As a consequence of this interpretation, in the East compartment occurs to the north of the synform-antiform pair interpreted by Rosière et al. (2006) plus two synformal folds, one to the south of the Carajás town and another one in the Serra Norte ridge. Thus, the folding system would be formed by a central antiform flanked by two synforms. In this context, the Serra Norte ridge synform is disconnected from this main system by a truncation structure located in the north of the Central granite (Orosirian) that is positioned in the hinge of an antiform. The figures 5 and 6 show that granitic intrusions have a relationship with up-dropped blocks and the development of truncation structures that fragmented the basin. As one can observe, the Estrela granite (Neoarchean) could be also positioned in an antiform hinge. I do not have data to inquire if these granitic intrusions of very different ages would have occupied the hinge of preexisting antiforms or contributed to their development. This line of interpretation reveals in the east end of the East compartment, another five tectonic down-dropped blocks, which can be interpreted as synforms. For the remainder of the basin, this interpretation shows that the Central Compartment is formed by two synforms separated in the center by a structural high. The West compartment is formed by two sets of synform-antiform-synform with axis plunging to the east and also separated by a structural high (Figures 5 and 6). In addition, to the north of the Central compartment, an isolated synform with structural direction controlled by the Cinzento Shear Zone occurs.

There is also the possibility that the modeled Carajás Basin shape could be the hybrid result of two tectonic processes; that is, an initial phase of vertical tectonics with formation of a rift internally structured in grabens and horsts, followed by a phase of compression and inversion of the basin with folds and reactivation of normal faults. The Figure 5 illustrates the

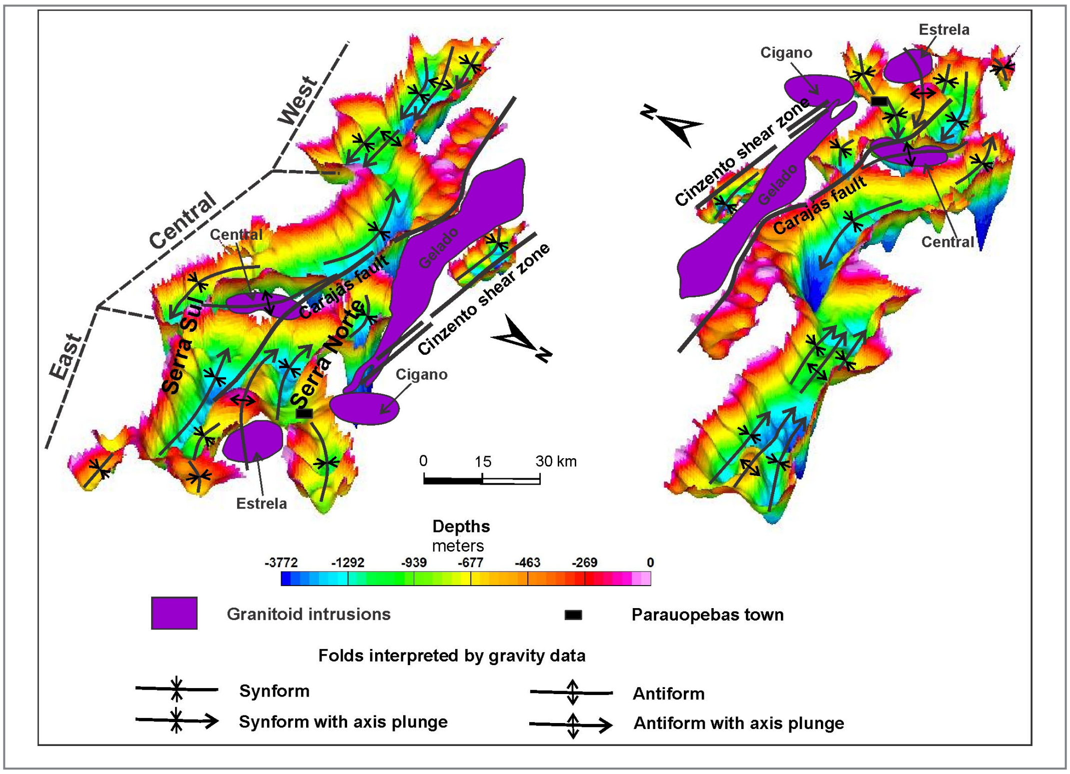

FIGURE 6 – Tridimensional views of the Carajás Basin structured in synform (down-dropped block) and antiform (up-dropped block) folds. The sense of axis plunge was interpreted as a sense of deepening of the blocks. The location of the Estrela, Gelado, Central and Cigano granitoids are showed.

possibility of superposition of the two types of deformation in correlation with metavolcano-sedimentary sequences. The maximum horizontal gradient would mark the locations where normal faults structured the basin in grabens and horsts and open space for deposition of the metavolcano-sedimentary sequences in the early stages of evolution of the Carajás Basin. Possibly, in the tectonic inversion phase, folding was facilitated and amplified by these pre-existing structures.

6. Conclusions

I present an interpretation of the gravity framework of the Carajás Province and a three-dimensional shape of the Carajás Basin from analyses and modeling of the first available regional coverage of aerogravity data. These data exposed different gravity signatures for Rio Maria and Carajás domains. The Rio Maria Domain gravity pattern is very compatible with the structure in dome-and-keels found in Archean cratons worldwide; while, in the Carajás Domain, the gravity pattern suggests a deposition of volcano-sedimentary rocks on elongated basins.

In the Carajás Basin, I observed that the metavolcano-sedimentary sequences have strong correlation with positive gravity anomalies. These positive anomalies were modeled by the forward method and the results show that the Carajás Basin is separated by intrabasinal highs in three compartments (East, Central and West) structured in down-dropped and up-dropped blocks with depths ranging from 500 to 3,700 m.

The results were compared with tectonic models of Carajás Basin evolution. The structuring of the basin by means of tectonics of the dome-and- keel type was considered unlikely. However, the performance of vertical tectonics forming grabens and horst is compatible with modeling results. In addition, a good correlation was obtained between the down-dropped and up-dropped blocks with synformal and antiformal folds, respectively.

These apparently conflicting results may suggest a model of evolution in which the formation of a rift structured internally in grabens and horsts occurred at the beginning of the evolution of the basin, whose reactivated structures facilitated and amplified the development of folds in the later phases of tectonic inversion.

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