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Gamma-ray spectrometry, magnetic and gravity signatures of Archean nuclei of the Borborema Province, Northeastern Brazil

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Abstract

Gamma-ray spectrometry, as well as magnetic and gravity data, are used to investigate the geophysical signatures of the Archean nuclei of the Borborema Province. Natural radioactivity, magnetic anomalies, and residual Bouguer gravity anomalies of the Archean nuclei exhibit distinct signatures in relation to adjacent Proterozoic domains. Gamma-ray spectrometry data reveal eTh enrichment in relation to K and eU contents in Archean units. Assuming that K and U were the dominant isotopes, this relative enrichment of eTh can be explained by the fact that Th radioisotopes have a longer half-life than the other two radionuclides and that 4.56 Ga has elapsed since Earth's formation. The intensity of the total magnetic gradient in Archean units is greater than in Proterozoic units in most nuclei. The Archean units underwent deformation and metamorphism in the Brasiliano/Pan-African Orogeny; therefore, the magnetic characteristics now observed in Archean mafic-ultramafic rocks, iron formations and gneiss-migmatite complexes are the joint result of their primary properties and the superposed effects of the orogeny. All Archean nuclei of the Borborema Province show positive residual Bouguer gravity anomalies. This could be due to the conservation of the main petrophysical properties of the Archean lithosphere, and their preservation during the intense granitization that occurred in the Brasiliano/Pan-African Orogeny. As magnetic and gravity methods provide information from depth, it is possible to infer the continuity of some Archean nuclei beyond the limits established by surface geological data. Based on these results, it will be possible to use geophysical signatures to investigate the possible existence of unknown Archean units in the province.

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1. Introduction

Globally, about 35 cratonic fragments of considerable sizes are known that preserve records of Archean rocks (e.g., Bleeker 2003; Condie 2007). However, the number of comparatively smaller additional fragments of this type is still unknown. In fact, identifying Archean crustal fragments is a difficult geological task, as they may have undergone regrouping and dispersion during the formation and destruction of continents and supercontinents (e.g., Nance et al. 2014; Pesonen et al. 2021). Paleomagnetic data have made a great contribution to tracking the trajectories of dispersed terranes over time (e.g., Evans and Pisarevsky 2008; Li et al. 2008). In addition, regional geophysical methods, such as teleseismics (e.g., Mandal and Biswa 2016; Costa et al. 2020), deep seismic refraction/reflection (e.g., Nguuri et al. 2001; Musacchio et al. 2004); magnetotellurics (Gokarn et al. 2004; Khoza et al. 2013), and gravity (e.g., Haas et al. 2023) have allowed to characterize the lithospheric structure of large cratons. In particular, gravity signatures have been used to compare Archean domains separated in space (e.g., Peschler et al. 2004).

Geophysical methods to investigate Archean granite-greenstone belts in large cratons have been frequently applied,

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too (e.g., House et al. 1999; Silva et al. 2003; Gwavava and Raganai 2009; Raganai 2012; Matos et al. 2022), due to the fact that a large part of global exploration and production of Fe, Cu, Au, Ni, IOCG, PGE-Cr, Sn and diamond occur in these belts (e.g., Groves and Barley 1994; Grainger et al. 2008; Angerer and Hagemann 2010; Xavier et al. 2012). Specifically, geophysical methods have been employed to characterize tectonic structures and to obtain two- and three-dimensional models for greenstone belts and associated magmatism (e.g., Peschler et al. 2004; Silvennoinen and Kozlovskaya 2007; Matos et al. 2022). Petrophysical contrasts between rocks with different lithological compositions have favored the use of indirect investigation methods, which may reduce the cost of mineral exploration (Schodde 2020).

In the Borborema Province of northeastern Brazil, eight small crustal blocks (areas between 500 and 4,220 km^2) with records of Archean rocks are known (Figure 1). Throughout the geological eras, these relatively small Archean fragments have suffered dispersion and regrouping and were subjected to deformation and metamorphism in the Brasiliano/Pan-African Orogeny (Brito Neves and Cordani 1991; Trompette 1994). Due to the heating effects imposed by this orogeny, it is not possible to use paleomagnetic data to track the trajectories of these blocks over previous geological eras. Therefore, it is difficult to establish the probable affiliations of these Archean nuclei. Various hypotheses about the origin of these nuclei have been raised based mainly on isotopic and lithological data. Frequently, the nuclei have been correlated with the São Francisco Craton, due to its paleo-proximity, for example regarding the Itabaiana (Rosa et al. 2020) and Entremontes (Ganade et al. 2021) nuclei. For the Alto Moxotó terrane in the central region of the Borborema Province, this affinity has been based on isotopic data (Ganade et al. 2021). However, these Archean nuclei are scattered throughout the province (Figure 1), thus also allowing affiliations with other cratons. For instance, for the Alto Moxotó terrane, Brito Neves et al. (2020) proposed a derivation from the Paleoproterozoic Supercontinent Columbia.

Given the complex geological evolution of these Archean nuclei, it is not expected that their original petrophysical properties have been fully preserved. For example, contrary to the metallogenic expectations for Archean rocks, so far no important mineral resources have been identified in these domains, exception for small Fe deposits in the Granjeiro II (Pitarello et al. 2019) and São José do Campestre (Dantas and Roig 2013; Roig and Dantas 2013) nuclei. Despite the proximity to Archean rocks, the small deposits of Au and Cr in de Troia-Pedra Branca nucleus are hosted in Paleoproterozoic rocks (Costa et al. 2019; Costa et al. 2021).

In this study, the gamma-ray spectrometric, magnetic and gravity signatures of the Archean nuclei in the Borborema Province have been investigated. The results show that natural radioactivity, magnetic anomalies, and residual Bouguer gravity anomalies exhibit distinct signatures in relation to the adjacent Proterozoic domains, in most cases. Furthermore, as magnetic and gravity methods can provide information in depth, it is possible to infer the continuity of some of these Borborema Archean nuclei beyond the limits established by surface geological data. Based on these results, it may be possible to use the identified pattern of geophysical signatures to track still unknown Archean units in the province.

2. Regional geological context

The Borborema Province is predominantly formed by a Paleoproterozoic gneissic-migmatite basement, surrounded by Neoproterozoic metasedimentary belts, in addition to small Archean nuclei (Figure 1). Because of its location between the São Francisco and West Africa cratons, it is a key region for understanding the tectonic evolution of the West Gondwana (Brito Neves and Cordani 1991; Trompette 1994). In the Mesozoic, the long orogenic belt developed in the Brasiliano/Pan-African orogeny and that extended continuously from Northeast Brazil to Togo, Benin, Nigeria and Cameroon in Africa (Trompette 1994) was separated by the formation of the Atlantic Ocean (e.g., Szatmari et al. 1987). This event had major impact on the lithosphere and left records of numerous coastal and inland sedimentary basins (e.g., Chang et al. 1988; Matos 1999).

The oldest ages for rocks in the Borborema Province were identified in eight small scattered nuclei (e.g., Dantas et al. 2004, 2013; Ganade et al. 2017; Pitarello et al. 2019; Lira Santos et al. 2017; Ferreira et al. 2020) (Figure 1): 1 - São José do Campestre, 2 - Campo Grande, 3 - Tróia-Pedra Branca, 4 - Granjeiro I, 5 - Granjeiro II, 6 - Entremontes, 7 - Alto Moxotó and 8 - Itabaiana-Simão Dias. These Archean units of the Borborema Province generally occur in continuity with Paleoproterozoic complexes (Dantas et al. 2004, 2013; Souza et al. 2016; Lira Santos et al. 2017; Ganade et al. 2017; Vale et al. 2023; Costa et al. 2019, 2021; Ferreira et al. 2020; Brito Neves et al. 2020). This association between Archean and Paleoproterozoic rocks suggests accretionary collision processes (e.g., Souza et al. 2016; Dantas et al. 2013; Neves 2015; Lira Santos et al. 2015, 2022; Ferreira et al. 2020; Amaral et al. 2023) that resulted in the formation of the basement of the Neoproterozoic sedimentary basins, which was later deformed and metamorphosed in the Brasiliano/Pan-African Orogeny (e.g., Van Schmus et al. 2003; Arthaud et al. 2008; Oliveira et al. 2010; Brito Neves et al. 2015, 2018; Caxito et al. 2016). This Neoproterozoic orogenic cycle was accompanied by extensive granitic magmatism that intruded all geological domains of the province (e.g., Ferreira et al. 1998; Santos and Medeiros 1999; Neves et al. 2000; Guimarães et al. 2004), but partially preserved the Archean nuclei, where records of such intrusions are rare. In turn, at the end of the orogenic cycle, pervasive shear strain caused widespread displacement of tectonic blocks (e.g., Araujo et al. 2013; Fossen et al. 2022).

3. Geological synthesis of the Archean nuclei in the Borborema Province

Variations in lithological composition can produce variations in the signatures of geophysical anomalies. Therefore, understanding the geological setting of each of the nuclei is essential for the interpretation of their geophysical anomalies (Figures 2, 3 and 4). Most of the radiometrically dated Archean rocks are orthogneisses, but some Archean ages have also been obtained from amphibolites and iron formations. The ages vary between Paleoarchean and Neoarchean, with a predominance of late Mesoarchean and Neoarchean ages.

3.1. São José do Campestre

This nucleus within the São José do Campestre Domain of the province (number1 in Figure 1, ~2,500 km^2 in extent)

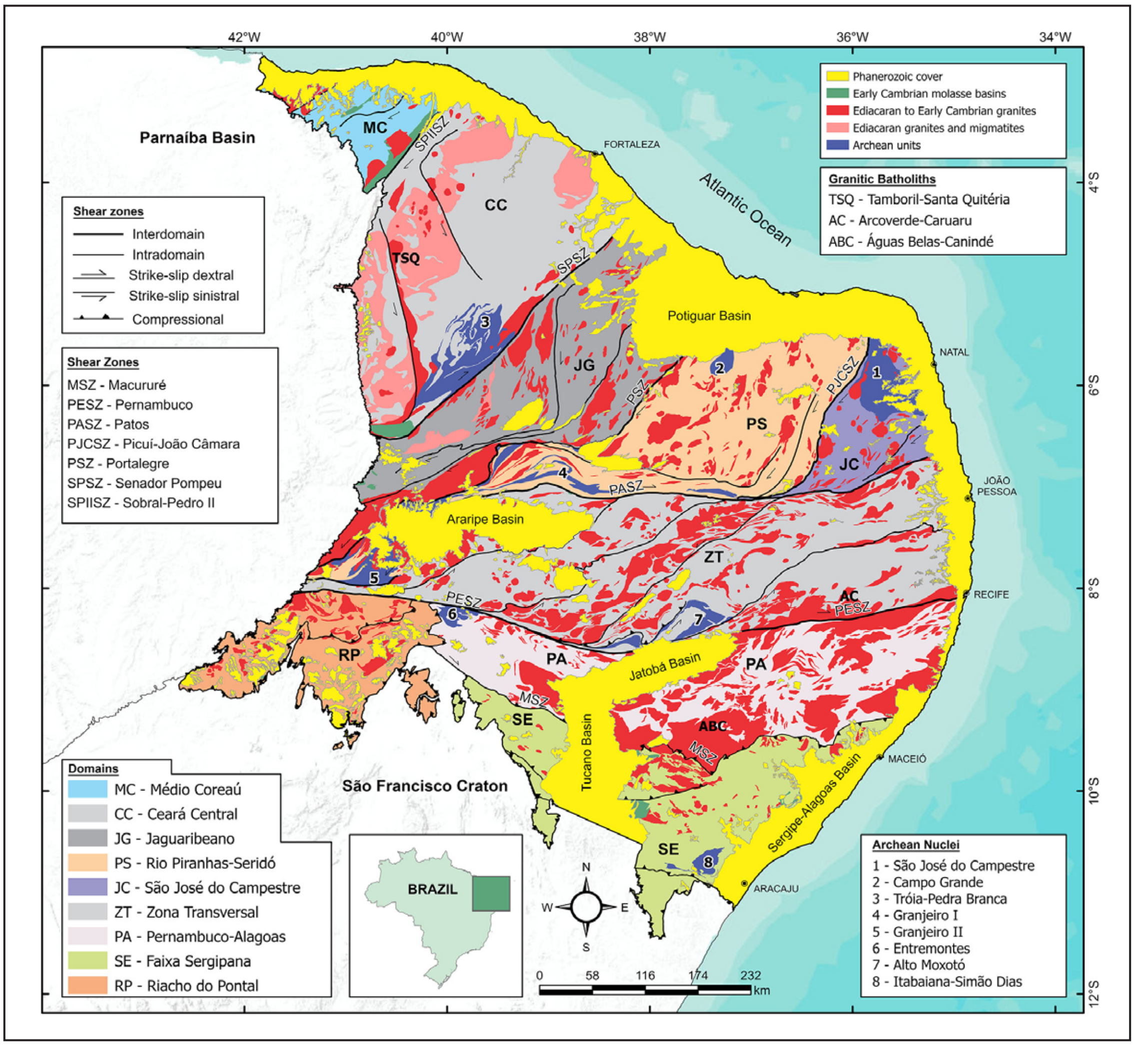

FIGURE 1 - Tectonic subdivision of the Borborema Province according to Delgado et al. (2003), with locations of the eight Archean nuclei (modified after Medeiros et al. 2021, also with updates from Santos et al. 2023).

is composed of lithotypes grouped into several complexes (Presidente Juscelino, Brejinho, Senador Elói de Souza, Riacho das Telhas and Serra Caiada) (e.g., Dantas et al. 2004, 2013; Souza et al. 2016) (Figure 1). The domain also includes the Bom Jesus Metatonalite, Teixeira Gneiss and São José do Campestre Granite (Dantas and Roig 2013; Roig and Dantas 2013). These complexes are mainly composed of orthogneisses, paragneisses, banded gneisses, migmatites, metagranitoids (granite-tonalite and trondhjemite), and metamafic/metaultramafic rocks (meta-gabbros, gabbronorites, pyroxenites, talc serpentine-chlorite schist and tremolite schist), besides metacarbonates and iron formations. Several Archean ages (U-Pb in zircon) in the interval of 3.41 to 2.66 Ga were obtained for orthoderived rocks. These ages were interpreted as the ages of crystallization of the protoliths (Dantas et al. 2004, 2013; Souza et al. 2016). This Archean nucleus is bordered in the south and west by Paleoproterozoic gneisses and migmatites, whereas in the north and east, the contacts are covered by Phanerozoic sedimentary rocks of the Potiguar Basin (Figure 1).

3.2. Campo Grande

The comparatively small Campo Grande Archean nucleus is located in the northern part of the province in Rio Piranhas Domain (number 2 in Figure1, ~500 km^2 in extent). Here, Ferreira et al. (2020) mapped migmatitic gneisses, which are generally tonalitic and granitic in composition, with intercalations of amphibolites and pyroxenites. All these rocks belong to the Campo Grande Complex. Ages from 2.98 to 2.66 Ga (U-Pb in zircon) were interpreted as crystallization ages for the protoliths (Ferreira et al. 2020). This nucleus is bordered to the east, south and west by Paleoproterozoic gneisses and migmatites of the Caicó Complex. In the north, the margin of the complex is covered by Phanerozoic sedimentary rocks of the Potiguar Basin (Figure 1).

3.3. Tróia-Pedra Branca

The relatively large Tróia-Pedra Branca nucleus is located in the Ceará-Central Domain of the province (number 3 in Figure 1, ~4,220 km^2 in extent). The nucleus is limited to the west by the Senador Pompeu Shear Zone (Figure 1) and comprises orthogneisses and migmatites of dioritic, tonalitic and granodiorite composition, along with intercalations of amphibolites, metaultramafic rocks, paragneisses, quartzites, calc-silicate rocks, and marbles. These rocks are grouped together into the Cruzeta Complex (Oliveira and Cavalcante 1993). Ganade et al. (2017) obtained U-Pb on zircon ages of 2.85–2.68 Ga from grey gneisses and amphibolites, that indicate two different episodes of Archean crust formation (2.85–2.77 Ga and 2.70–2.68 Ga), which could indicate flat to steep subduction transition.

3.4. Granjeiro I and Granjeiro II

The Archean rocks of the Granjeiro Complex are separated into two segments: the first is positioned adjacent to the Patos Lineament in the Rio Piranhas-Seridó Domain (Granjeiro I, number 4 in Figure 1, 850 km2 in extent); the second occurs adjacent to the Pernambuco Lineament in the Zona Transversal Domain (Granjeiro II, number 5 in Figure 1, ~1,400 km2 in extent). In both segments, the Archean units are composed of banded orthogneisses with tonalitic and granodioritic compositions, with intercalations of metamafic and metaultramafic rocks, and more rarely, paragneisses with lenses of iron formations, quartzites and felsic metavolcanic rocks. U-Pb on zircon ages obtained from orthogneisses of this complex range from 3.35 to 2.59 Ga (Silva et al. 1997; Freimann 2014; Ancelmi 2016; Pitarello et al. 2019; Vale et al. 2023). Continuity between the two units beneath the Araripe Basin sedimentary rocks has been attributed to the common tectonic control exerted by a NE-SW splay of the E-W shear zones of the Patos Lineament (Santos et al. 2023).

3.5. Entremontes

The Entremontes nucleus is located in the Pernambuco-Alagoas Domain (number 6 in Figure 1, ~545 km^2 in extent). The nucleus is composed of orthogneisses of granitic-granodioritic composition, which contain lenses of amphibolites that are sometimes migmatized. All these rocks are grouped together into the Entremontes Complex (Cruz 2015). Only one Neoarchean age of 2.73 Ga (U-Pb in zircon) was obtained for a granitic orthogneiss (Cruz 2013). This age was attributed to the crystallization of the protoliths to these rocks. The northern margin of the Entremontes Complex is limited by the dextral transcurrent shear zones of the Pernambuco Lineament (Figure 1), whereas the São Francisco craton occurs at the southern margin.

3.6. Alto Moxotó

This Alto Moxotó nucleus is located in the Transversal Zone Domain (number 7 in Figure 1, ~1,160 km2 in extent). The Archean units form the Riacho das Lajes Suite and Mulungu-Feliciano Complex. The Riacho das Lajes Suite is composed of metagranitoids and migmatized orthogneisses of granodioritic-tonalitic and sometimes monzogranitic composition. U-Pb on zircon ages obtained for members of this suite are 2.64 and 2.63 Ga (Lira Santos et al. 2017). The Mulungu-Feliciano Complex (Lira Santos et al. 2017) comprises dioritic to monzogranitic migmatites and orthogneisses with intercalations of augen gneiss (monzogranitic) and dioritic metamafic rocks. A U-Pb age in zircon of 2.60 Ga was determined for dioritic orthogneiss (Brito Neves et al. 2020). The Archean nucleus is bordered by Paleoproterozoic and Mesoproterozoic units and is delimited to the south by the Pernambuco Shear Zone, and to the north by the Serra de Jabitacá Shear Zone.

3.7. Itabaiana-Simão Dias

The Itabaiana-Simão Dias nucleus occurs in the Sergipano Domain (number 8 in Figure 1, ~645 km2 in extent) and is composed of tonalitic to granitic and migmatite orthogneisses, with enclaves or bands of amphibolites and metagabbros. These rocks are grouped into the Itabaiana-Simão Dias Complex (Teixeira 2014). This nucleus contains gneiss-migmatite rocks that are surrounded by Neoproterozoic quartzites. This pattern leads some researchers to propose that the nucleus represents a basement dome (e.g., D'el-Rey Silva 1995). Two Archean U-Pb in zircon ages were obtained for the rocks of the central part of this possible dome. One was determined for tonalitic orthogneisses to 2.73 Ga and was interpreted as the age of crystallization of the protolith (Santiago et al. 2017); the other age of 2.83 Ga (Rosa et al. 2020) was determined for a melanosome sample from a trondhjemitic-migmatitic gneiss. Based on these results, Rosa et al. (2020) proposed that this nucleus might be correlated with Mesoarchean rocks of the São Francisco Craton.

4. Geophysical datasets and interpretation approach

Gamma-ray spectrometric and magnetic data were collected by the Geological Survey of Brazil (SGB-CPRM) in several projects between 2006 and 2011 (see Figure 2B in Oliveira et al. 2023b). Natural radioactivity (total count, K, eTh and eU channels) and total magnetic field data were measured along N-S flight lines spaced at 500 m at a height of 100 m. Control lines were surveyed at 10 km spacing in the E-W direction. The resulting datasets are available at https://geoportal.cprm.gov.br/geofisica. An exception to this standard survey design was made for the area of the Potiguar Basin, where PETROBRAS surveyed only magnetic data (Project 4045 in Figure 2B in Oliveira et al. 2023b), using flight lines spaced at 2000 m and a flight height of 500 m.

Data from the individual channels for K, eTh and eU from all projects was interpolated, integrated and leveled in a unified 125 m x 125 m grid by Correa (2020). However, to compare the statistics of gamma-ray spectrometry data for the Archean nuclei, the original datasets were used. We emphasize that instead of measuring the energy intensities of K, Th and U, the energy intensities of the daughter radioisotopes (^{40}K for potassium, ^{208}Tl for thorium and ^{214}Bi for uranium) were measured. For this reason, the use of the letter "e", before the symbols for uranium (eU) and thorium (eTh), indicates that the concentrations values are equivalent. Thus, the radioelements U and Th will be presented here in two ways: with and without the equivalent designation. In the first manner (with), we are referring to eTh and eU contents estimated from the airborne geophysical data, whereas in the second manner (without), we refer to Th and U contents measured by conventional geochemical methods. In this study, we used a ternary composition in false RGB color, where Red, Green and Blue colors represent K, eTh and eU, respectively (Figure 2). When interpreting the values of the ternary composition, it should be observed that the content of a radioelement is always expressed in relative terms; that is, if the absolute content of a radioelement is small in a given area, but is relatively larger than the others in this area, the ternary composition will be expressed in terms of an enrichment. When comparing different areas, note that if all radioelement contents are relatively high/low in a certain area, as compared to the other areas, the resulting color is white/black. It is worth mentioning that the Borborema Province has actually a semi-arid climate, which favors the preservation of relatively fresh exposures. As a result, gamma-ray spectrometry surveys provide high-quality data, allowing a resolution good enough to reliably compare relative concentrations of radioelements.

Figure 3 shows the resulting magnetic anomaly map, after a processing flow that included removing the International Geomagnetic Reference Field (IGRF), leveling, interpolating the individual projects onto a 125-m grid (using the bigrid method), and joining the individual grids into a single grid (using the gridknit method).

The residual Bouguer gravity anomaly map in Figure 4 is an update of the maps shown by Oliveira and Medeiros (2012, 2018). As in these previous publications, regional-residual separation was done by removing a wavelength component of 300 km from the Bouguer anomaly map, which included satellite data from the adjacent oceanic area. However, relative to the previously published maps, the Bouguer anomaly used here includes new data surveyed since 2018 by the Brazilian Institute of Geography and Statistics (IBGE) and the Geological Survey of Brazil (SGB-CPRM). The spatial distribution of measurement points is given in Oliveira et al. (2023b). The new data were also referenced to the IGSN-71 standard and to the MAPGEO15 geoid model (IBGE). Furthermore, the Bouguer anomalies were calculated using the density value of 2,670 kg/m3, including terrain correction. Moreover, here, an interpolation was performed on a 5 km x 5 km grid using the minimum curvature method with a blanking radius of 20 km. All gravity data used in this study are in the public domain and can be obtained from the BNDG-ANP (*Banco Nacional de Dados*

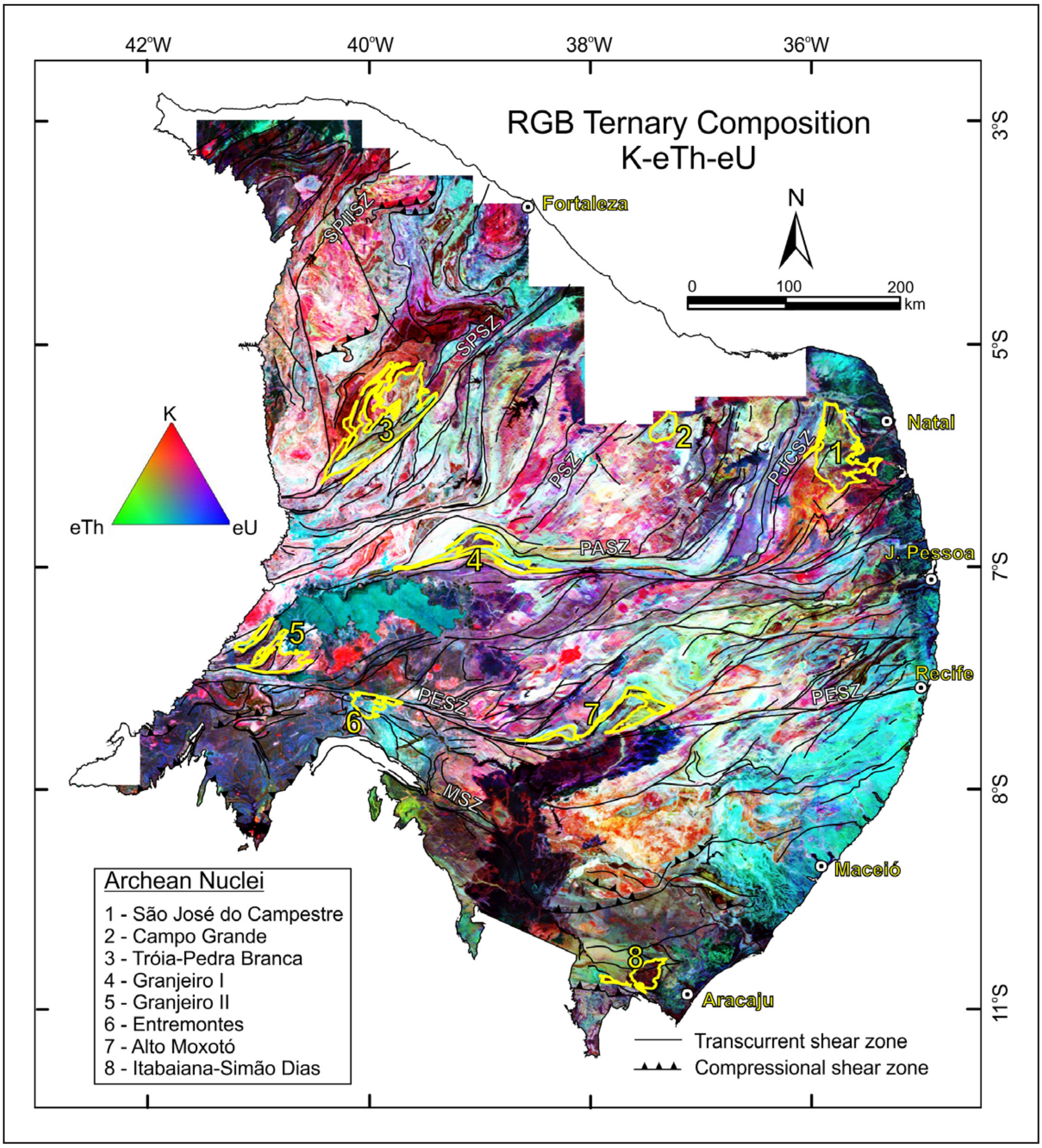

FIGURE 2 - R(red)G(green)B(blue) ternary composition map of the K-eTh-eU contents of the Borborema Province, superposed with the main structures and the locations of the Archean nuclei. Merging and leveling of the grids was done by Correa (2020). See the caption of Figure 1 for abbreviations of the shear zones.

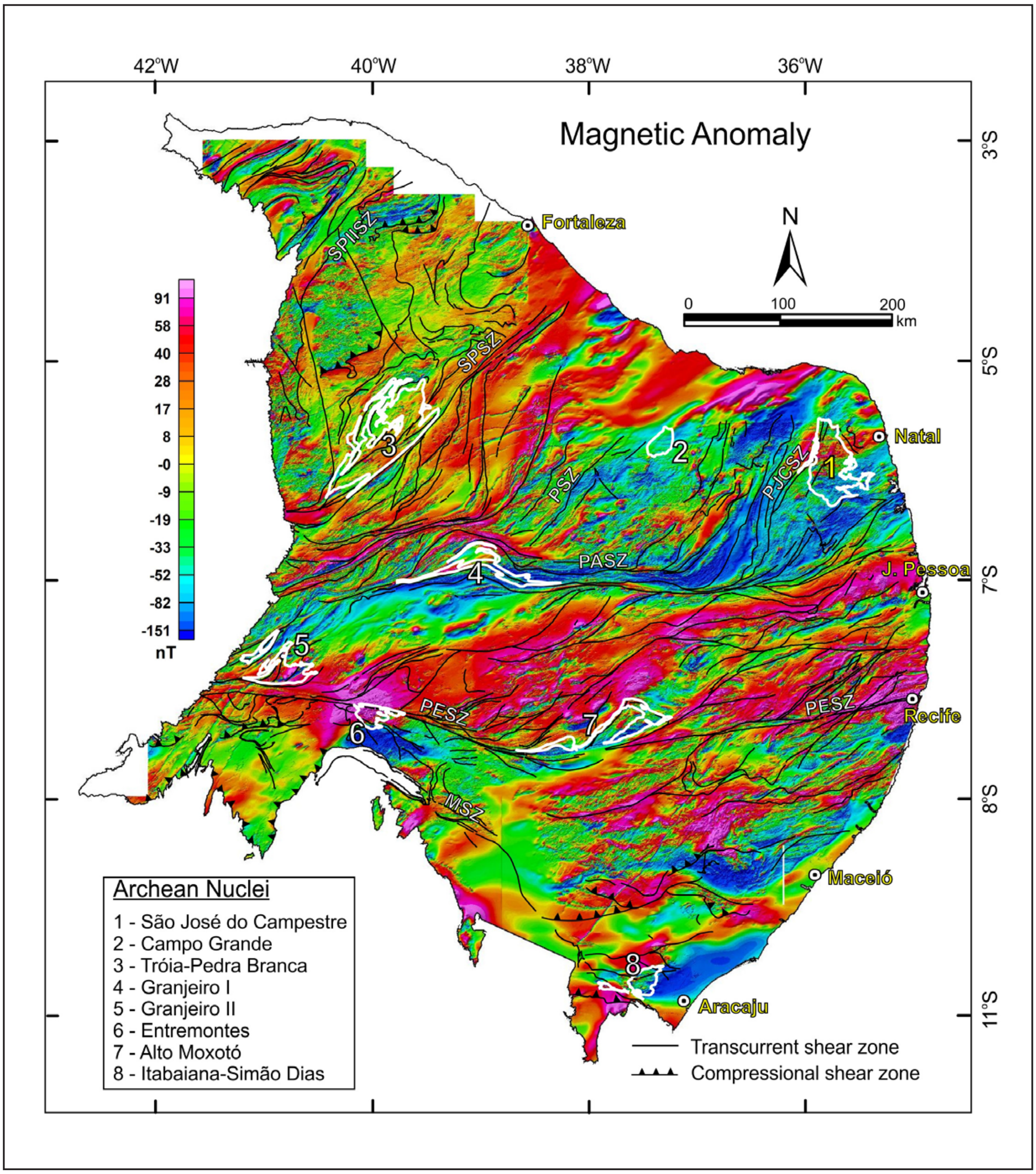

FIGURE 3 - Magnetic anomaly map of the Borborema Province, superposed with the main structures and the locations of the Archean nuclei. See the captions for Figure 1 for abbreviations of the shear zones.

Gravimétricos da Agência Nacional de Petróleo) at https://www.gov.br/anp/pt-br/assuntos/exploracao-e-producao-de-oleo-e-gas/dados-tecnicos/legislacao-aplicavel/bndg-banco-nacional-de-dados-gravimetricos), IBGE (http://www.ibge.gov.br) and SGB-CPRM (https://geosgb.sgb.gov.br) websites.

When performing statistical analyses of geophysical datasets to compare the signatures of the various Archean nuclei, we used the values of the residual Bouguer anomaly, the total magnetic gradient, and original gamma-ray spectrometry (i.e., the K-eTh-eU values from each project). The respective grids were cut and recorded as ASCII files, to group the geophysical data into three sets: the first set takes into account the entire area of the Borborema Province, excluding only the Archean nuclei and sedimentary basins (SET1); the second set includes only the areas of Archean nuclei (SET2), and statistics are calculated separately for each nucleus; the third set combines the isolated statistics of SET2 into a single statistics (SET3). We summarize the results in Figures 5 and 6; note that these two figures compare the three sets of statistics in different manners. Figure 5 compares the statistics of SETs 1 and 2, whereas Figure 6 compares the statistics of SETs 1 and 3. In these figures, the individual medians are given, and the variation around each median is reported in three manners: first, by the colored bars, which represent the values between the first (25%) and third (75%) quartiles; second, by the thick solid lines, which represent the median absolute deviation value; and third, by the thin lines, which record the outliers.

5. Results - geophysical signatures of the Borborema Archean nuclei

We begin by describing the geophysical signatures of each nucleus separately. Afterward, in the discussions, we will make a general comparison, highlighting common or dissimilar aspects between the nuclei (Figures 5 and 6). When interpreting gravity data, emphasis was placed on amplitude and wavelength parameters. When interpreting magnetic data, emphasis was placed on the intensity of the total gradient of the anomalies. Note that using the (amplitude of the) total magnetic gradient avoids taking into account the dependence of the anomaly's polarity on magnetic latitude.

5.1. São José do Campestre

Archean rocks of the São José do Campestre nucleus (Figure 7A) are correlated with greenish tones in the RGB ternary composition (Figure 7B), indicating relative enrichment in eTh (Profile A-B in Figure 7E). Interspersed in this color pattern are areas presenting reddish-brown tones, which are related to rocks slightly enriched in K (Figure 7B). These can be correlated with orthogneisses and metagranitoids (granite, tonalite and trondhjemite). At sites of origin of dated samples, there is a predominance of enrichment in K (Figure 7B). Metamafic/metaultramafic rocks and iron formations are the sources of the linear and elliptical magnetic anomalies seen in Figure 7C. Magnetic lineaments trend in four main directions

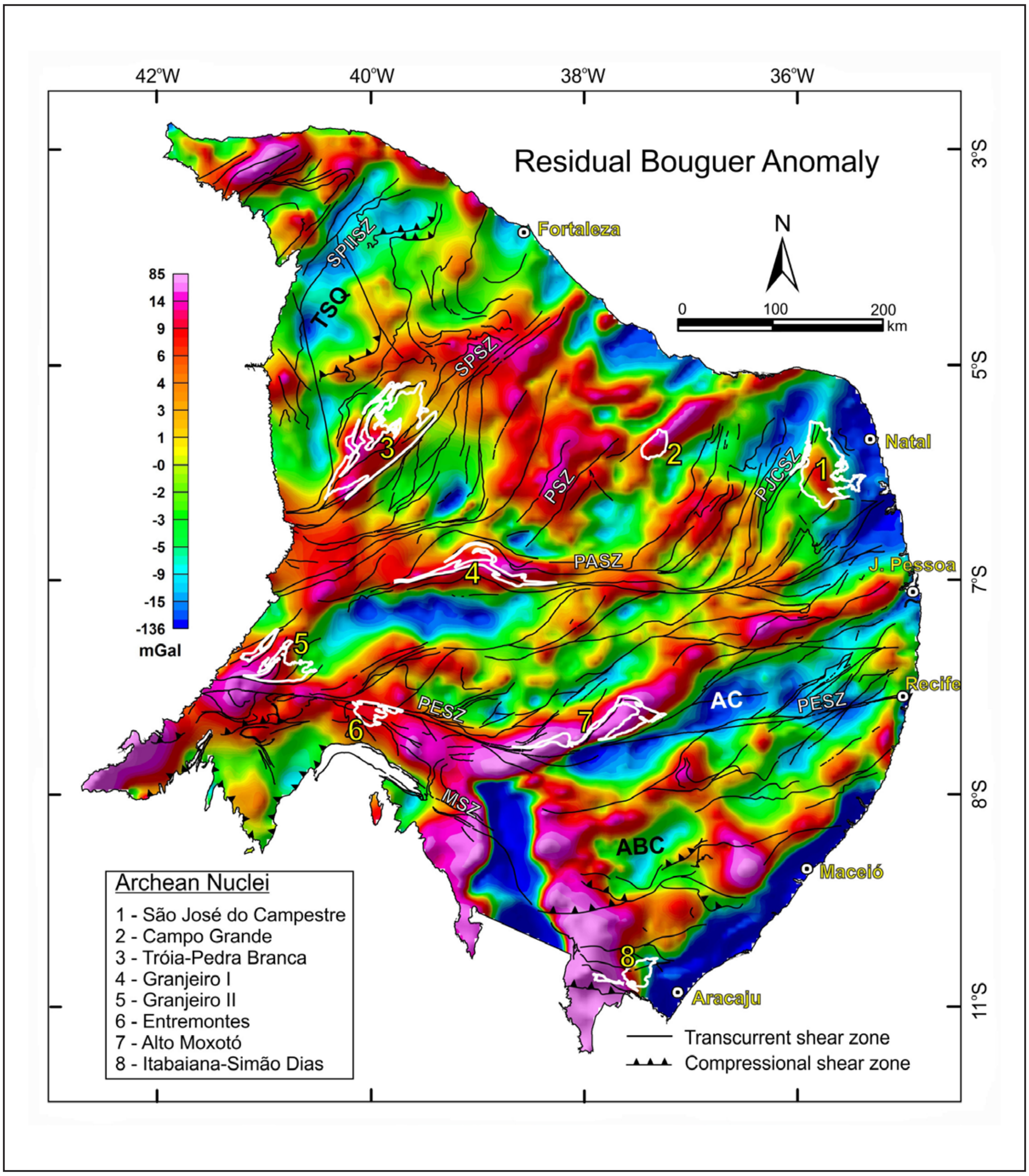

FIGURE 4 - Residual Bouguer gravity anomaly map of the Borborema Province, superposed with the main structures and the locations of the Archean nuclei. Granitic batholiths: TSQ - Tamboril-Santa Quitéria, AC - Arcoverde-Caruaru, ABC - Águas Belas-Canindé. See the captions for Figure 1 for abbreviations of the shear zones.

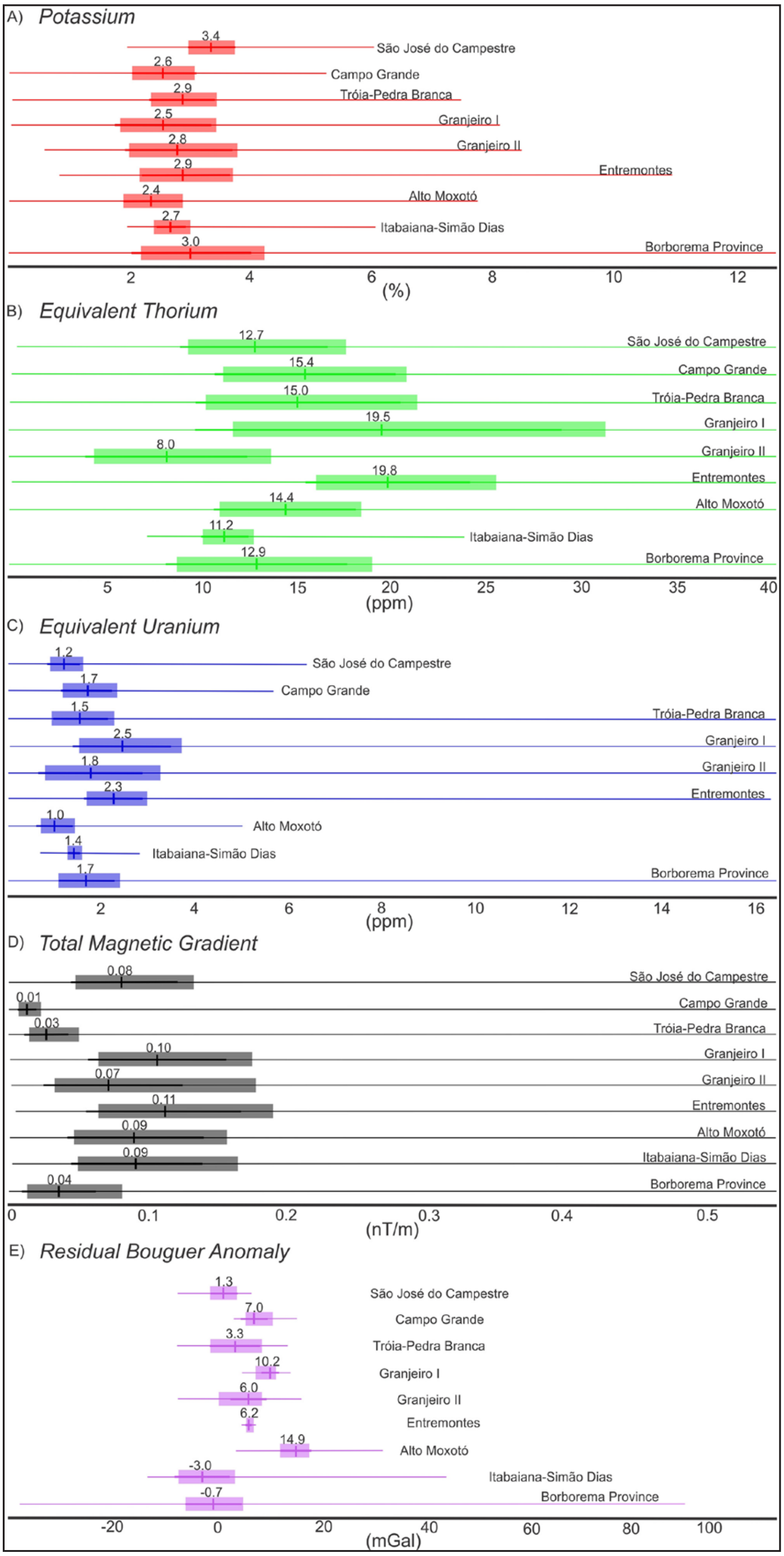

FIGURE 5 - Box plot reporting the statistics of SETs 1 and 2 of the following geophysical signatures of rocks in Borborema Province: A) Potassium (%); B) Equivalent Thorium (ppm); C) Equivalent Uranium (ppm); D) Total magnetic gradient (nT/m); E) Residual Bouguer gravity anomaly (mGal). SET1 takes into account the entire area of the Borborema Province, excluding the Archean nuclei and sedimentary basins. SET2 includes only the areas of Archean nuclei and statistics are calculated separately for each nucleus. See the text for details about the statistics presented.

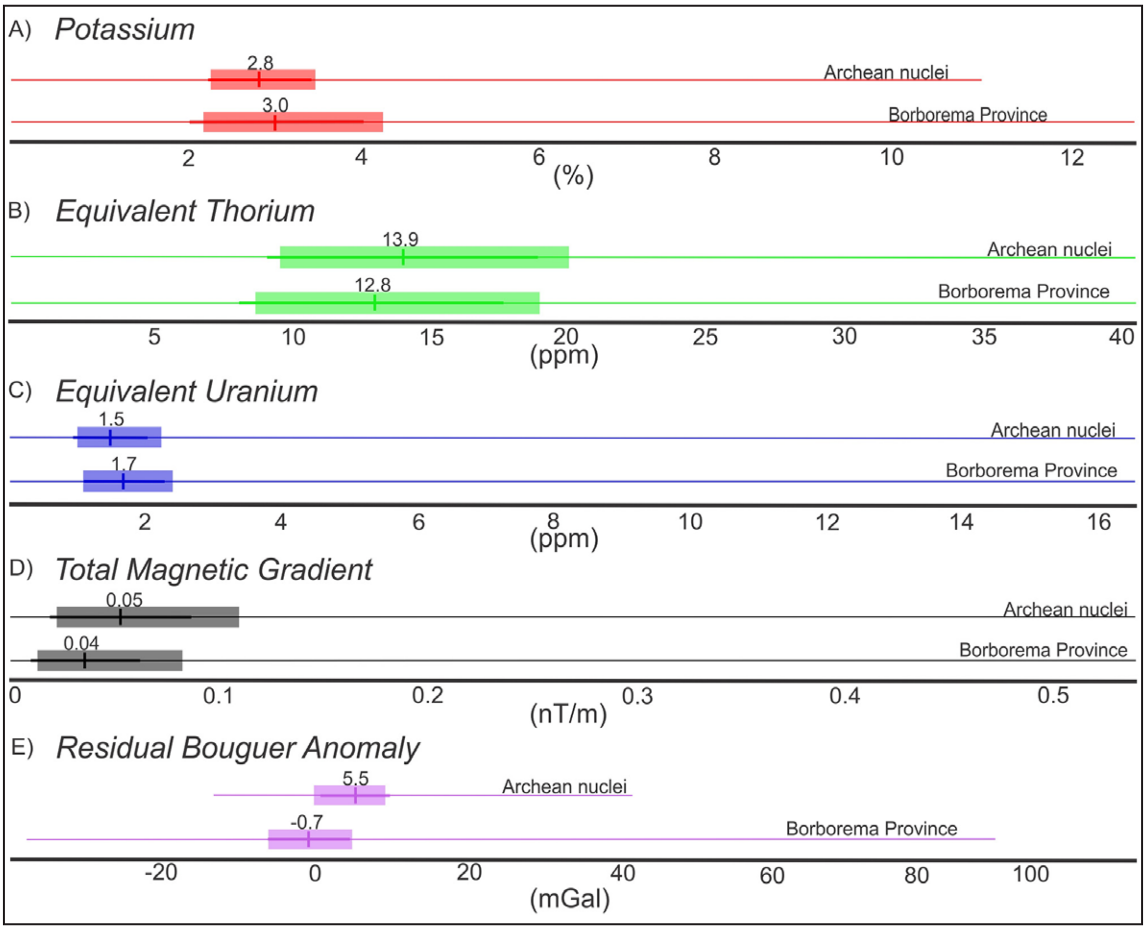

FIGURE 6 - Box plot reporting the statistics of SETs 1 and 3 of the following geophysical signatures of rocks in Borborema Province: A) Potassium (%); B) Equivalent Thorium (ppm); C) Equivalent Uranium (ppm); D) Total magnetic gradient (nT/m); E) Residual Bouguer gravity anomaly (mGal). SET1 takes into account the entire area of the Borborema Province, excluding the Archean nuclei and sedimentary basins. SET3 combines the isolated statistics of SET2 shown in Figure 5 into a single statistic. See the text for details above the statistics presented.

(Figure 7C): i) NNE-SSW lineaments, which are correlated with the deformation trends of the Picuí-João Câmara Shear Zone; ii and iii) intersecting NW-SE and NE-SW lineaments, which are correlated with the directions of tectonic foliations inside the Archean nucleus; and iv) straight E-W lineaments, which are correlated with dikes of the Rio Ceará-Mirim Magmatism (CMD in Figure 7C). In the gravity map (Figure 7D), a good correlation of the Archean rocks with a residual positive anomaly is evident; the anomaly has amplitude and wavelength of about 20 mGal and 80 km, respectively (Profile A-B in Figure 7E). The western and southern boundaries of the gravity anomaly delimit the Archean nucleus from the Paleoproterozoic domains. The eastern and northern boundaries of the gravity anomaly correspond to the contact with the Potiguar Basin (Figure 7A). Compared to the Proterozoic rocks of the Borborema Province, this Archean nucleus is characterized by higher values of the medians of K content, total magnetic gradient and positive residual Bouguer gravity anomaly, whereas the median values of eTh and eU content are lower (Figure 5).

5.2. Campo Grande

Archean rocks of the Campo Grande nucleus (Figure 8A) can be correlated in the RGB ternary composition map (Figure 8B) with semicircular interspersed areas of greenish tones, which are associated with rock and soils enriched in eTh (Profile C-D in Figure 8E). Note that the distribution of radioelements follows curved lineaments with a concavity to the northeast, which propagate from the interior of the nucleus to the southwest, beyond the geological limit as suggested by the geochronological data (Figure 8). The Archean rocks do not present an expressive total magnetic gradient (Figure 5D), indicating that they are relatively depleted in magnetic minerals (Figure 8C and Profile C-D in Figure 8E). On the other hand, the NE-SW magnetic lineament associated with the shear zone at the northwest edge of the nucleus, and the E-W lineaments related to dikes of the Ceará-Mirim magmatism, are remarkable. Note also that outside the area demarcated as Archean, a good correlation is observed between curved magnetic and radiometric lineaments (Figures 8B and 8C). In the residual Bouguer gravity map (Figure 8D), a positive NE-SW trending anomaly is observed, which has an amplitude of 6 mGal and a wavelength of 30 km (Profile C-D in Figure 8E). The main NE-SW-trending anomaly is related to a dextral shear zone that defines its northwestern boundary (Figure 8). The positive gravity anomaly continues to the south and northeast beyond the limits of the Archean nucleus. Compared to the Proterozoic rocks of the Borborema Province, this nucleus has higher median values of eTh and eU content, and a positive

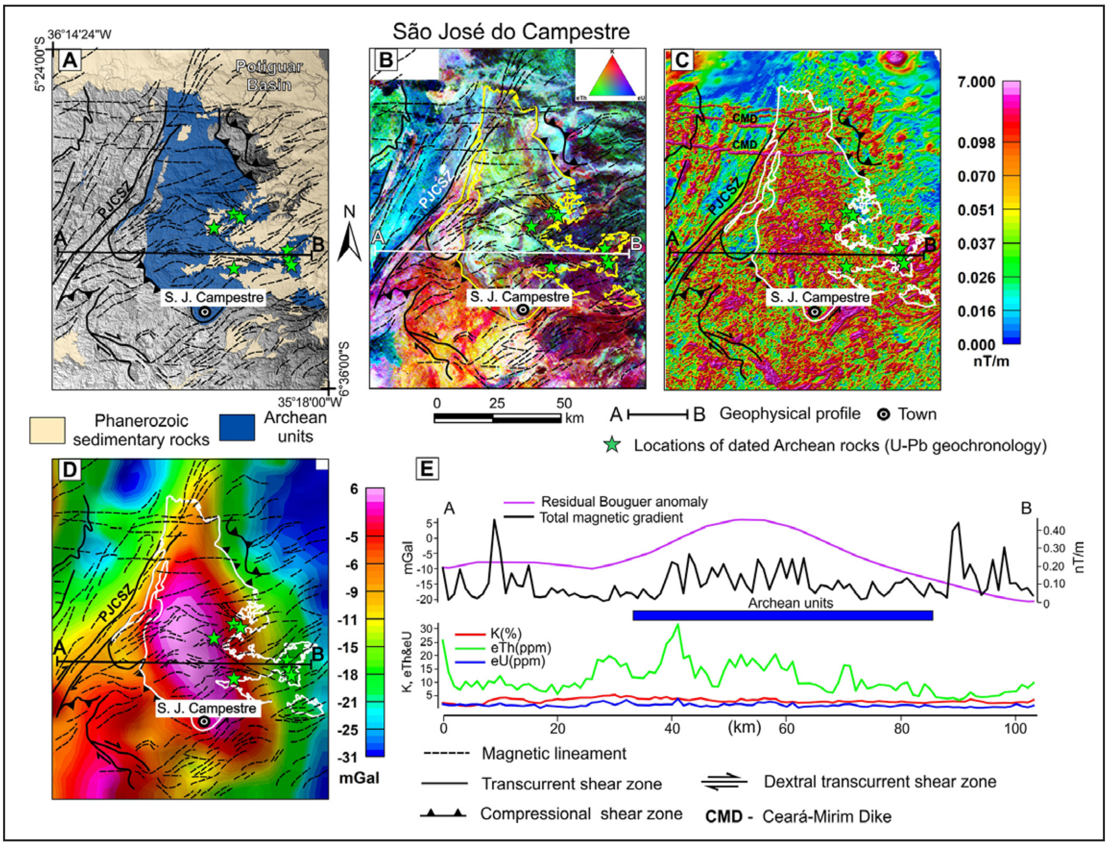

FIGURE 7 - Geophysical signatures of the São José do Campestre nucleus, with superposed tectonic structures, magnetic lineaments, and also showing the locations of dated samples (Dantas et al. 2004, 2013; Souza et al. 2016): A) Archean units and Phanerozoic sedimentary rocks; B) RGB ternary composition of the K-eTh-eU contents; C) Total magnetic gradient; D) Residual Bouguer gravity anomaly; E) Profile A-B, length of the profile on the graph is multiplied by 2.3. Abbreviations: PJCSZ - Picuí - João Câmara Shear Zone, CMD - Ceará-Mirim Dikes.

residual Bouguer gravity anomaly, and smaller median values of K content, besides a lower total magnetic gradient (Figure 5).

5.3. Tróia-Pedra Branca

Archean rocks of the Tróia-Pedra Branca nucleus (Figure 9A) are correlated in the RGB ternary composition image (Figure 9B) with greenish colors, indicating significant eTh enrichment (see also Figure 5B and Profile E-F in Figure 9E). This RGB pattern follows the orientation of lineaments in the NE-SW direction, which is the main orientation of the foliation of the rocks. In the west and north parts of the nucleus, there is a predominance of enrichment in K (Figure 9B). Note the clear contrast between the relative enrichment in eTh of the Archean nucleus with the K-enriched rocks (reddish tones) that surround it (Figure 9B). The Archean rocks do not have a significant magnetic signature (Figure 9C), indicating that they are depleted in magnetic minerals (Profile E-F in Figure 9E, and Figure 9C). However, magnetic lineaments oriented in the NE-SW direction stand out, and follow the tectonic foliation and the shear zones (Figure 9C). In the gravity map (Figure 9D), there is a significant positive residual Bouguer anomaly oriented in NE-SW direction, with an amplitude of 18 mGal and a wavelength of 90 km (Profile E-F in Figure 9E). The boundaries of this anomaly are well correlated with the orientations of two regional shear zones, the Senador Pompeu on the southeast boundary and the Tauá on the west boundary (Figure 9). The shape of the gravity anomaly suggests that the volume of dense rocks is greater in the southern part of the nucleus and gradually decreases towards the north, where the anomaly becomes negative (Figure 9D). Compared to the Proterozoic rocks of the Borborema Province, this nucleus has higher median values of eTh content and a positive residual Bouguer gravity anomaly, and lower median values of K, eU content, and weaker total magnetic gradient (Figure 5).

5.4. Granjeiro I

Archean rocks of the Granjeiro I nucleus (Figure 10A) are correlated in the RGB ternary composition map (Figure 10B) with greenish tones, indicating a relative enrichment of eTh. Locally, small parts of the Archean nucleus show either relative enrichment in eU (blue tones in Figure 10B) or in the three radioelements (K-eTh-eU) (whitish tones in Figure 10B). The Archean terrane has magnetic lineaments that can be correlated with shear zones (Figure 10C). In the gravity map, a positive residual Bouguer anomaly in the E-W direction is observed, with an amplitude of 14 mGal and a wavelength of 40 km (Figure 10D and Profile G-H in Figure 10E). This anomaly bends slightly to the north, following the trend of the tectonic foliation, which is locally strongly controlled by the Patos Shear Zone (Figure 10D). Compared to the Proterozoic rocks of the Borborema Province, in this nucleus, only the K content has a lower median value (Figure 5).

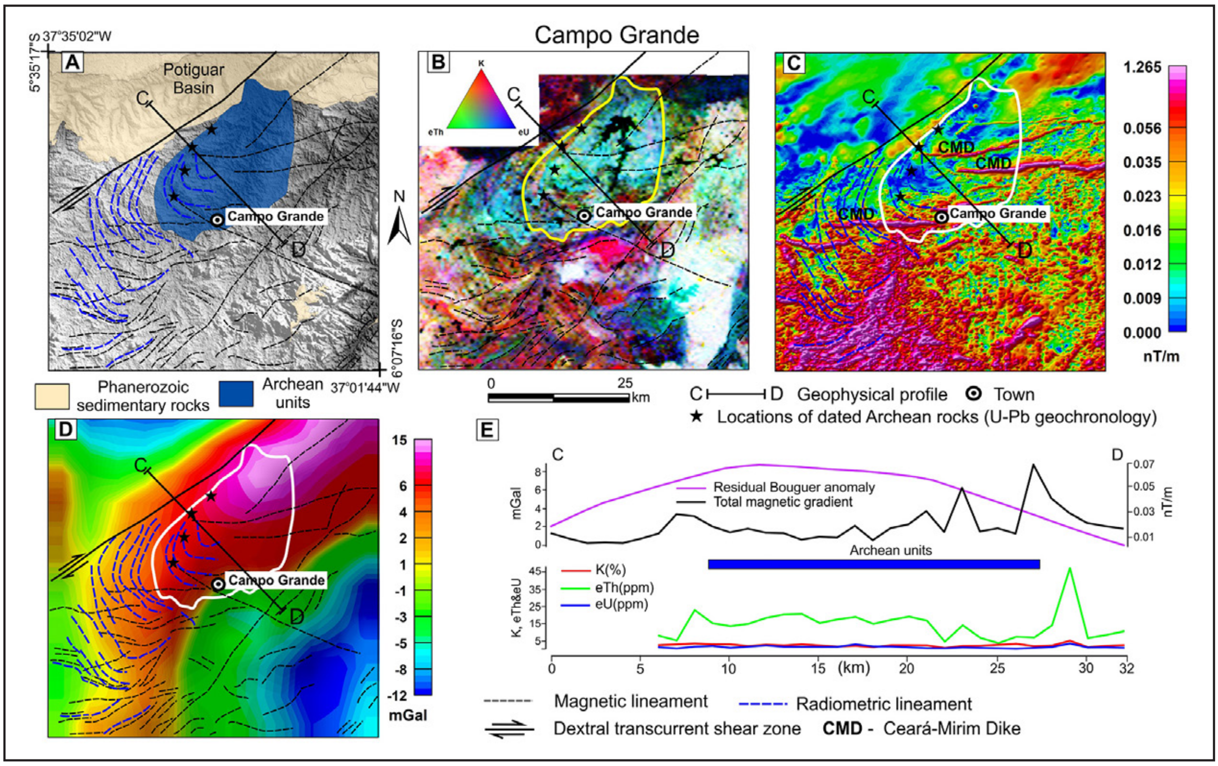

FIGURE 8 - Geophysical signatures of the Campo Grande nucleus, with superposed tectonic structures, magnetic and radiometric lineaments, and locations of Archean samples with age determinations (Ferreira et al. 2020): A) Archean units and Phanerozoic sedimentary rocks; B) RGB ternary composition of the K-eTh-eU contents; C) Total magnetic gradient; D) residual Bouguer gravity anomaly; E) Profile C-D, length of the profile on the graph is multiplied by 3.3. Abbreviation: CMD - Ceará-Mirim Dikes.

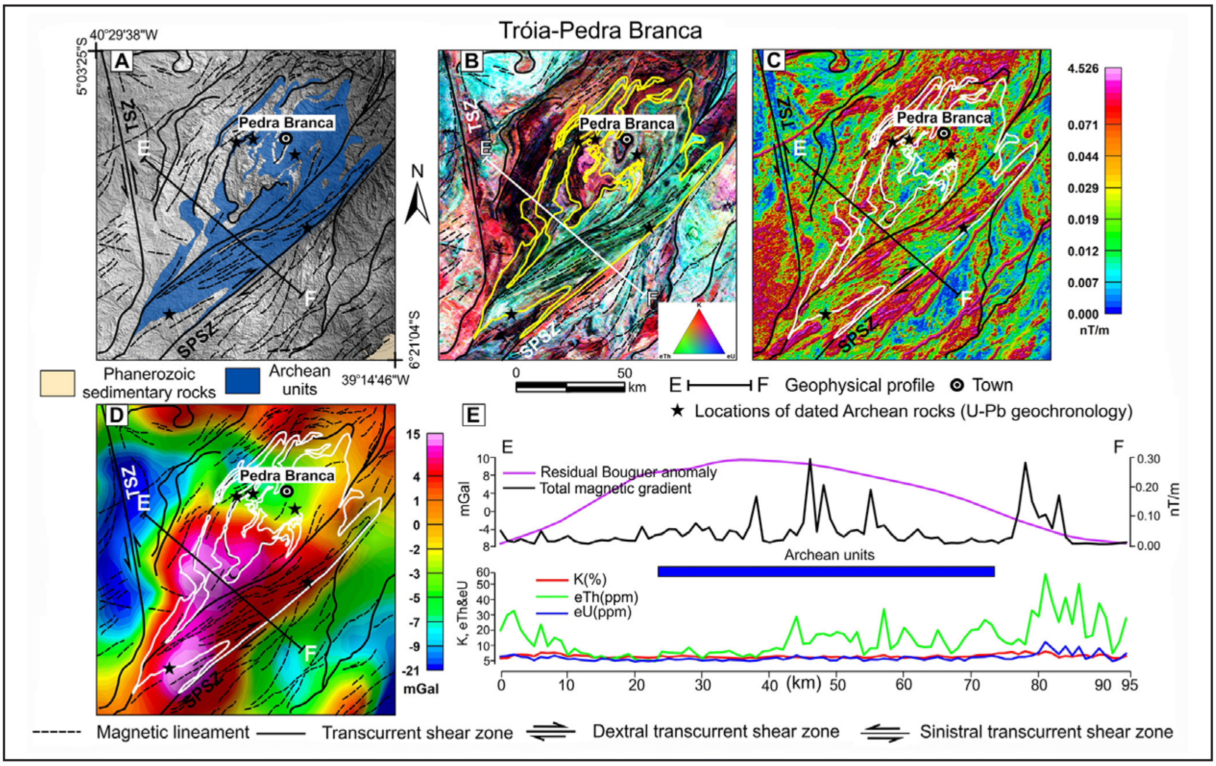

FIGURE 9 - Geophysical signatures of the Troia-Pedra Branca nucleus, with superposed tectonic structures, magnetic lineaments, and locations of Archean samples with age determinations (Ganade et al. 2017): A) Archean units and Phanerozoic sedimentary rocks; B) RGB ternary composition of the K-eTh-eU contents; C) Total magnetic gradient; D) residual Bouguer gravity anomaly; E) Profile E-F, length of the profile on the graph is multiplied by 3. Abbreviations: SPSZ - Senador Pompeu Shear Zone, TSZ - Tauá Shear Zone.

5.5. Granjeiro II

Archean rocks of the Granjeiro II nucleus (Figure 11A) are correlated in the RGB ternary composition map (Figure 11B) with alternating bands of relative enrichment in eTh (greenish tones in Figure 11B) and K (reddish tones in Figure 11B). These bands are separated by areas with whitish tones that indicate enrichment in the three radioelements. At locations of samples with age determinations, there is relative enrichment in K (Figure 11B). Generally, the Archean rocks are characterized by a low total magnetic gradient (Figure 11C); however, locally, there are elongated banded iron formations with higher total magnetic gradient. These formations follow the direction of NE-SW shear zones (BIF in Figure 11C and in Profile I-J in Figure 11E), generating magnetic lineaments in this direction that bend to the west near the Pernambuco Shear Zone (Figure 11C). In the gravity map, a well-defined positive residual Bouguer anomaly runs in a NE-SW direction, with an amplitude of 7 mGal and a wavelength of 60 km (Figure 11D and Profile I-J in Figure 11E). However, the boundaries of this anomaly do not coincide with the surface geological boundaries of the nucleus, although the anomaly covers most of the mapped area of the nucleus (Figure 11D). Compared to the Proterozoic rocks of the Borborema Province, this nucleus has higher median values of eU content, a positive residual Bouguer gravity anomaly and total magnetic gradient, and lower median values of K and eTh contents (Figure 5).

5.6. Entremontes

The Entremontes nucleus (Figure 12A) exhibits a more complex RGB pattern (Figure 12B), with areas indicating relative enrichment in the three radioelements. The relative enrichment in K is associated with Archean granitoids (Cruz 2015), whereas areas with relative enrichments in eTh and eU are correlated with colluvial-eluvial sedimentary covers and laterites (Cruz 2015). In the magnetic anomaly map (Figure 3), the Entremontes Complex is correlated with a regional anomaly, suggesting the existence of a block of magnetic rocks that extend to great depths in the upper crust (Cruz 2015). The magnetic lineaments are oriented into a dominant SSE-NNW direction, according to the tectonic foliation of the Pernambuco Shear Zone (Figure 12C). In the gravity map, the nucleus is associated with a positive residual Bouguer anomaly with an amplitude of 2 mGal and a wavelength of 30 km (Figure 12D and Profile L-M in Figure 12E). The southern limit of this anomaly corresponds to the boundary between the São Francisco Craton and the Pernambuco Alagoas Domain, whereas the northern limit correlates with the Pernambuco Shear Zone (Figure 12D). Note that the peaks of the magnetic and gravity anomalies are not coincident. Thus, the boundaries of high density and high magnetic sources probably do not coincide (Profile L-M in Figure 12E). Compared to the Proterozoic rocks of the Borborema Province, in this Archean nucleus, only the K content has a lower median value (Figure 5).

5.7. Alto Moxotó

Archean rocks of the Alto Moxotó nucleus (Figure 13A) are correlated in the RGB ternary composition map (Figure 13B) with greenish colors, indicating a relative enrichment in eTh. However, the migmatized metagranitoids and orthogneisses of the Riacho das Lajes Suite are correlated with areas where relative enrichment of the three radioelements occurs, as indicated by the whitish colors (A in Figure 13B). Archean rocks have a significant magnetic signature (Figure 13C). Generally, the magnetic signature is defined by elongated lineaments trending in the NE-SW direction, which can be correlated with tectonic foliation and shear zones (Figure 13C). In the gravity map, Archean units are correlated with a positive residual Bouguer anomaly following a NE-SW

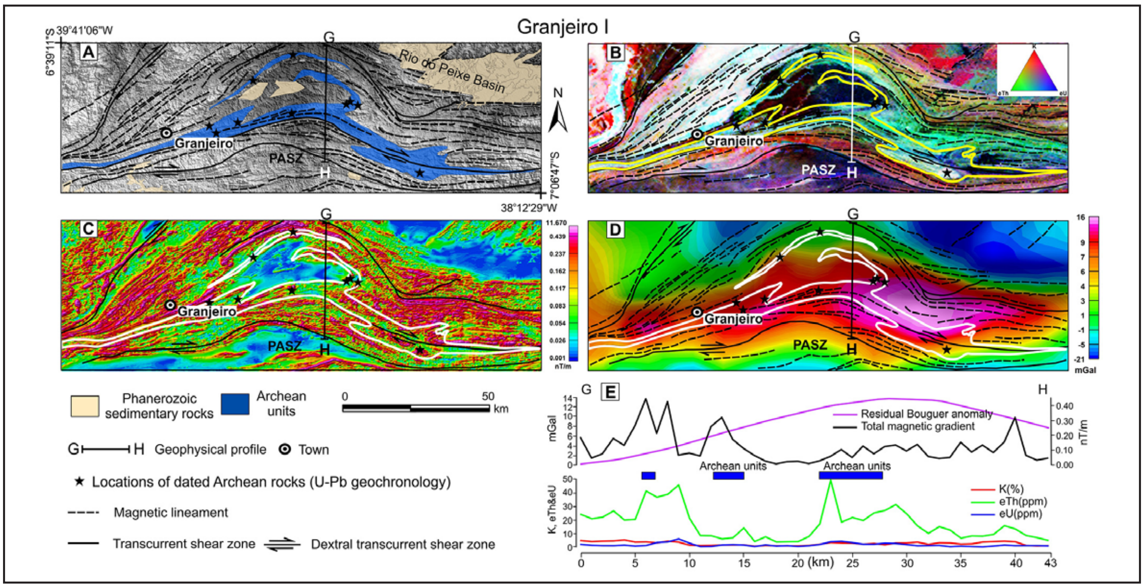

FIGURE 10 - Geophysical signatures of the Granjeiro I nucleus, with superposed tectonic structures, magnetic lineaments, and locations of Archean samples with age determinations (Silva et al. 1997; Freimann 2014; Ancelmi 2016; Pitarello et al. 2019): A) Archean units and Phanerozoic sedimentary rocks; B) RGB ternary composition of the K-eTh-eU contents; C) Total magnetic gradient; D) Residual Bouguer gravity anomaly; E) Profile G-H, length of the profile on the graph is multiplied by 3.8. Abbreviations: PASZ - Patos Shear Zone.

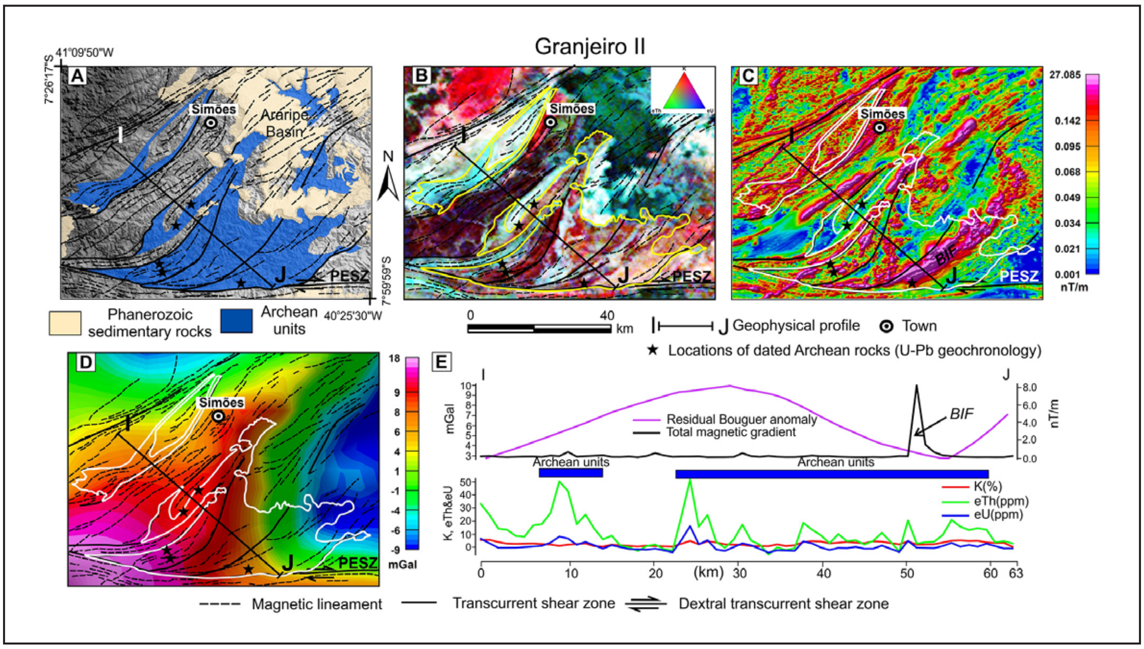

FIGURE 11 - Geophysical signatures of the Granjeiro II nucleus, with superposed tectonic structures, magnetic lineaments, and locations of Archean samples with age determinations (Pitarello et al. 2019; Vale et al. 2023): A) Archean units and Phanerozoic sedimentary rocks; B) RGB ternary composition of the K-eTh-eU contents; C) Total magnetic gradient; D) Residual Bouguer gravity anomaly; E) Profile I-J, length of the profile on the graph is multiplied by 2.4. Abbreviations: PESZ - Pernambuco Shear Zone, BIF - Banded Iron Formation.

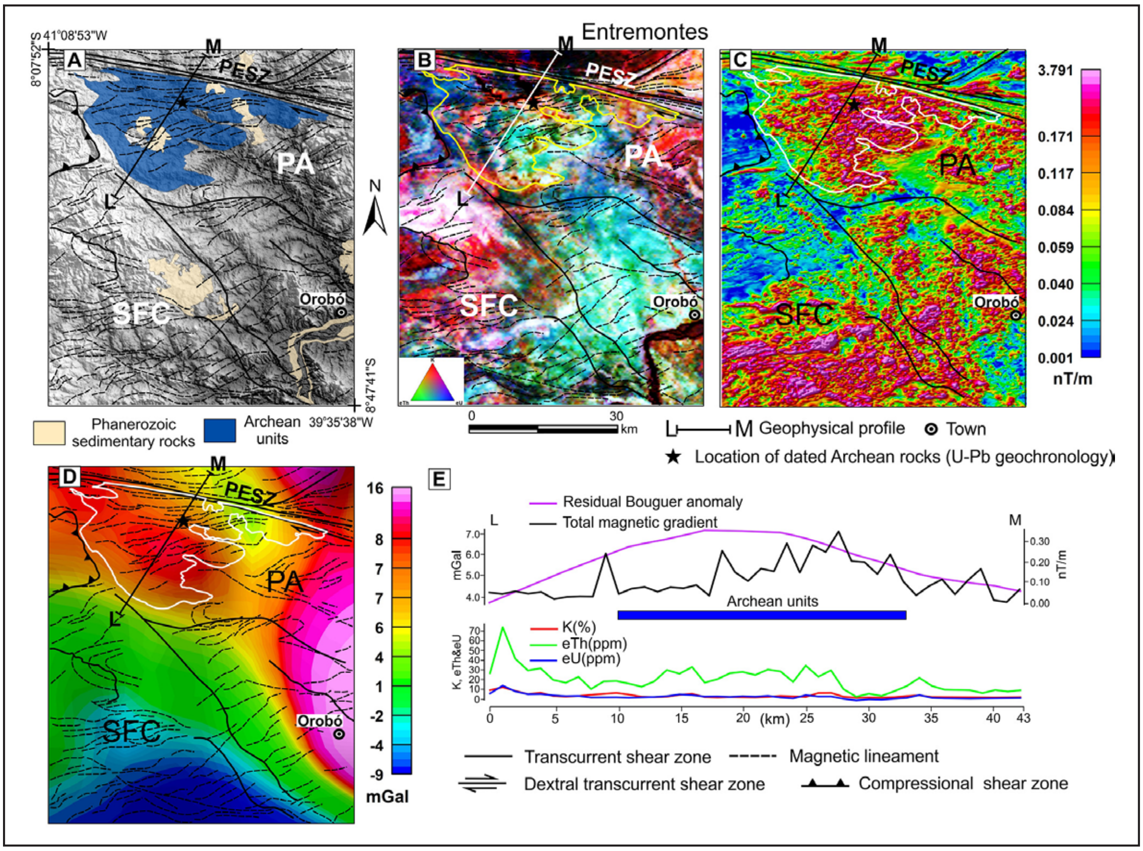

FIGURE 12 - Geophysical signatures of the Entremontes nucleus, with superposed tectonic structures, magnetic lineaments, and locations of Archean samples with age determination (Cruz 2013): A) Archean units and Phanerozoic sedimentary rocks; B) RGB ternary composition of the K-eTh-eU contents; C) Total magnetic gradient; D) Residual Bouguer gravity anomaly; E) Profile L-M, length of the profile on the graph is multiplied by 3. Abbreviations: PESZ - Pernambuco Shear Zone, SFC - São Francisco Craton, PA - Pernambuco - Alagoas Domain.

direction, with an amplitude of 15 mGal and a wavelength of 50 km (Figure 13D and Profile N-O in Figure 13E). These anomaly directions can be correlated with the Pernambuco and Congo-Cruzeiro do Nordeste shear zones (Figure 13D). The gravity sources can be attributed to metamafic rocks and iron formations. Note that there is a reasonable spatial correlation between gravity and magnetic anomalies (Figure 13D and Profile N-O in Figure 13E), indicating that density and magnetic sources may have common geometry. Compared to the Proterozoic rocks of the Borborema Province, this nucleus has higher median values of eTh content, and a higher total magnetic gradient, and a positive residual Bouguer gravity anomaly, whereas the median values of K and eU content are lower (Figure 5).

5.8 Itabaiana-Simão Dias

Archean rocks of the Itabaiana-Simão Dias nucleus (Figure 14A) are correlated in the RGB ternary composition map (Figure 14B) with areas relatively enriched in K, due to the dominance occurrence of felsic orthoderived rocks. Note that Archean rocks do not contrast with the surrounding metasedimentary rocks in regard to the eTh content (Figure 14B and Profile P-Q in Figure 14E). The total magnetic gradient map (Figure 14C) shows that Archean rocks have a strong magnetization, likely caused by a relative enrichment in magnetic minerals (Profile P-Q in Figure 14E). The interpretation of Oliveira et al. (2023a) of the magnetic signature of this nucleus (better known as Itabaiana-Simão Dias Dome; e.g., D'el-Rey Silva 1995) suggests that this crustal block continues to the northeast beneath the sedimentary rocks of the Sergipe-Alagoas Basin. The northern limit of the crustal block is correlated with the Mocambo and São Miguel do Aleixo shear zones (see figure 3 in Oliveira et al. 2023a). From regional gravity maps (Figure 4), it is possible to infer that this nucleus is located in the intermediate part of a regional anomaly associated with the boundary between the São Francisco Craton and the Sergipano Belt (Oliveira and Medeiros 2018; Oliveira et al. 2023a). According to the gravity modeling of Oliveira et al. (2023a), this crustal block (density around 2,900 kg/m^3; see figures 5 and 7 in Oliveira et al. 2023a) dips northwards and is juxtaposed against the upper low-angle interface of the São Francisco Craton. In the residual Bouguer gravity map (Figure 14D), Archean units are correlated with a positive anomaly with an amplitude of 5 mGal and a wavelength of 40 km (see also Profile P-Q in Figure 14E). Compared to the Proterozoic rocks of the Borborema Province, in this nucleus, only the total magnetic gradient has a relatively higher median value (Figure 5).

6. Discussion

6.1. Causes of Th enrichment in the Archean units

Gamma-ray spectrometric signatures of most of the Borborema Province Archean nuclei revealed relative enrichment of eTh, in comparison with the Proterozoic rocks (Figure 6). There are two exceptions to this trend. The first is related to the Itabaiana-Simão Dias nucleus, which is depleted in the three radioelements (Figure 5B), and the second case is related to the Granjeiro II area (Figure 5B). In all nuclei, K enrichment is local. Likewise, enrichment in the K-eTh-eU combinations is also restricted to specific areas. Statistical data demonstrate that, when considering only Archean rocks, the median of eTh content varies between 8.0 and 19.8 ppm, with the

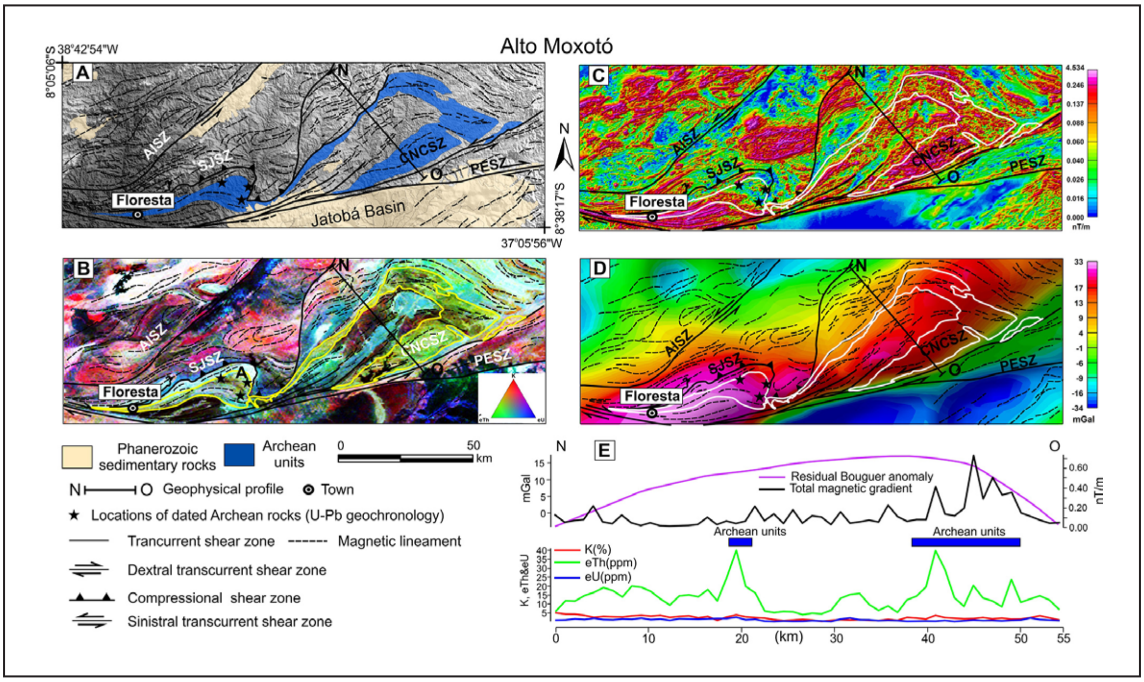

FIGURE 13 - Geophysical signatures of the Alto Moxotó nucleus, with superposed tectonic structures, magnetic lineaments, and locations of Archean samples with age determinations (Lira Santos et al. 2017; Brito Neves et al. 2020): A) Archean units and Phanerozoic sedimentary rocks; B) RGB ternary composition of the K-eTh-eU contents; C) Total magnetic gradient; D) Residual Bouguer gravity anomaly; E) Profile N-O, length of the profile on the graph is multiplied by 3.6. Abbreviations: PESZ - Pernambuco Shear Zone, CCNSZ - Congo-Cruzeiro do Nordeste Shear Zone, SJSZ - Serra de Jabitacá Shear Zone; AISZ - Afogados da Ingazeira Shear Zone.

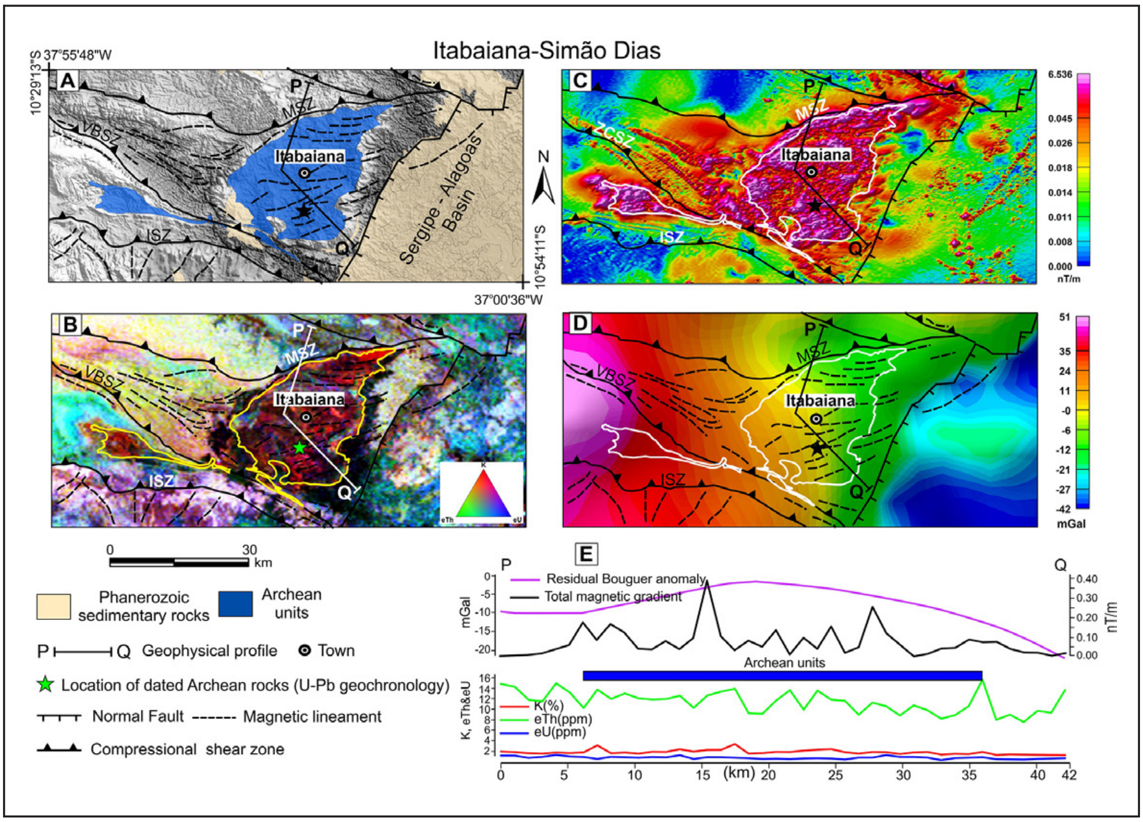

FIGURE 14 - Geophysical signatures of the Itabaiana-Simão Dias nucleus, with superposed tectonic structures, magnetic lineaments, and locations of Archean samples with age determinations (Santiago et al. 2017; Rosa et al. 2020). A) Archean units and Phanerozoic sedimentary rocks; B) RGB ternary composition of the K-eTh-eU contents; C) Total magnetic gradient; D) Residual Bouguer gravity anomaly; E) Profile P-Q, length of the profile on the graph is multiplied by 3. Abbreviations: MSZ - Mocambo Shear Zone, VBSZ - Vaza Barris Shear Zone, ISZ - Itaporanga Shear Zone.

highest average content occurring in the Entremontes nucleus (Figure 5). The main sources of eTh are orthoderived gneiss-migmatite complexes with metagranitic/tonalitic intrusions.

According to Dickson and Scott (1997), the average Th content in the upper crust is 12 ppm; usually, mafic and felsic rocks have contents below and above this value, respectively. However, in the Borborema Province, correlations of gamma-ray spectrometric data (e.g., Cavalcante et al. 2016; Uchôa Filho et al. 2019; Santos et al. 2020; Gomes et al. 2021; Costa et al. 2023) with geology reveal that granitic rocks of the Brasiliano/Pan-African Orogeny usually do not show relative enrichment of eTh, although in many of these bodies, potassium and uranium are high and the thorium as well (see the whitish areas in Figure 2).

In metamorphic rocks, the eTh content can vary greatly. In addition, it was observed that the eTh content is depleted compared to the eU content in most Neoproterozoic metasedimentary units of the Borborema Province (e.g., Cavalcante et al. 2016; Uchôa Filho et al. 2019; Santos et al. 2020; Gomes et al. 2021; Costa et al. 2023). However, the eTh content is enriched in the Paleoproterozoic gneiss-migmatite complexes that compose the basement of the metasedimentary units, for instance, in the Alto Moxotó terrane (Lira Santos et al. 2023) and the Rio Piranhas-Seridó domain (Costa et al. 2023).

The relative enrichment of eTh (Figure 6) observed in the Archean terranes of the Borborema Province can be explained by taking into account the decay rate of the radioelements and the heat flux produced over time. It is known that U and K radioisotopes have shorter half-lives than Th radioisotopes (e.g., Turcotte and Schubert 2002). Thus, the radiogenic heat production from U and K radioisotopes was higher in the Archean, and decreased over time, whereas the heat production from Th radioisotopes decay remained more or less constant (table 4-2 and figure 4-4 in Turcotte and Schubert 2002). As the actual amount of these radioelements in the Earth's crust depends on their initial volumes and rates of decay, the Th currently has a relatively higher relative abundance in older rocks because of its longer half-life. The research done by Chiarini et al. (2024) in central Brazil is a good example of tectonic gamma-ray spectrometric signature in Archean terranes.

For rocks and soils exposed to the surface that may have undergone significant geochemical changes (e.g., Dickson and Scott 1997), the standard trend discussed above may not be strictly applicable. For example, local concentrations of Th and U can occur due to geological processes involving transportation of these elements, absorption in colloidal clays, formation of iron oxides, and lateritization of soils, or by zircon and monazite concentration in alluvium or colluvium (e.g., Dickson and Scott 1997). Even for deep-seated rocks, magmatic and hydrothermal events may be able to modify the concentrations of these radioelements, favoring enrichment of one of them in relation to the others (e.g., Shives et al. 2000; Airo 2002; Maden and Akaryal 2015; Mamouch et al. 2022).

6.2. Magnetic signatures and their sources in the Archean units

Compared to the remainder of the Borborema Province, the total magnetic gradient is higher in the São José do Campestre, Granjeiro I, Granjeiro II, Entremontes, Alto Moxotó and Itabaiana nuclei, and lower in the Campo Grande and Troia-Pedra Branca nuclei (Figure 5D). Thus, in most nuclei, the total magnetic gradient is persistently high (Figure 5D). In addition, even in the other nuclei where the total magnetic gradient is moderate to low, areas with a high total magnetic gradient may occur, usually along well-defined lineaments. Locally, the source rocks are Archean, as, for example, the iron formations of the Granjeiro II nucleus (BIF in Figure 11C and Profile I-J in Figure 11E). In other cases, these rocks are not Archean, as in the Campo Grande nucleus, where the main magnetic signatures are produced by the dikes of the Cretaceous Ceará-Mirim Magmatism (CMD in Figure 8C). Statistical data show that, when considering only the Archean rocks, the median of the total magnetic gradient varies between 0.01 and 0.11 nT/m, with the largest gradients occurring in the Entremontes nucleus (Figure 5D). Considering all nuclei, the total magnetic gradient of the Archean rocks shows a median 20% higher than that of the Proterozoic rocks of the Borborema Province (Figure 6D). The main sources of the magnetic anomalies are gneisses and migmatites, mafic/ultramafic rocks, and iron formations.

The association of greenstone belt and intrusive tonalite-trondhjemite-granite (TTG) suites represents one of the oldest records in Earth's history, occupying a large part of the exposed areas of Archean crust (e.g., Condie 2007 and references therein). The metavolcanosedimentary sequences of greenstone belts are the main hosts of mafic/ultramafic rocks, and iron formations (e.g., Brandl et al. 2006 and references therein). In some cases, these rocks are part of the stratigraphy of elongated basins (rifts) that do not present the typical geometry of greenstone belts, such as, for example, the Carajás Basin in the Amazonian Craton (e.g., Pinheiro and Holdsworth 1997; Pinheiro and Holdsworth 2000; Oliveira 2018). In most studies, greenstone belts are correlated with magnetic anomalies of medium to large amplitudes, which have elongated and sinuous (sometimes semicircular) shapes, involving komatiites, iron formations, mafic/ultramafics and serpentinites (e.g., House et al. 1999; Wellman 2000; Silva et al. 2003; Gallardo and Thebaud 2012; Ramotoroko et al. 2016). Felsic intrusive suites often appear as cores of elliptical shape that are surrounded by the greenstone belt (e.g., House et al. 1999; Fayol et al. 2016). These intrusive suites do not show the same magnetic characteristics for different Archean terranes. In some cratons, they exhibit low magnetic intensity, for example, in the Filabusi and Madibe-Kraaipan terranes of Zimbabwe (e.g., Raganai 2012) and Kaapvaal (e.g., Ramotoroko et al. 2016) cratons. In other cratons, magnetic intensities may be medium to high, as in the Kambalda-Widgiemooltha area of Australia (e.g., House et al. 1999), the Masvingo Craton of Zimbabwe (e.g., Gwavava and Raganai 2009), and the Superior Province of the Canadian Shield (e.g., Hattori 1987).

The ultramafic rocks, iron formations, and gneiss-migmatite complexes contained in the Archean nuclei of the Borborema Province can be separate fragments of granite-greenstone belts that formed large cratons. We stress, however, that there are still no consistent studies that prove this hypothesis. Iron formations and mafic/ultramafic rocks often have high contents of Fe and, therefore, may yield high magnetic susceptibility values. Furthermore, according to Grant (1985), serpentinization of mafic rocks and an increase in the degree of metamorphism of iron formations may increase the intensity of magnetization. In the field, we observed that magnetic susceptibility measurements of some of these rocks gave high values (~1000 x 10^{-3}SI, Oliveira et al. 2011), in agreement with their related magnetic anomalies. In addition, measurements of magnetic susceptibility in gneiss-migmatite complexes have demonstrated that an important source of anomalies in the Alto Moxotó nucleus (Figure 13C) are migmatized orthogneisses with coarse-grained magnetite in large quantities (Oliveira and Marinho 2013). This suggests that anatectic events may have favored the formation of magnetic minerals, possibly due to the widespread availability of Fe and Mg pre-existing in the rocks that were migmatized. This hypothesis does not agree with the prediction of Grant (1985) that there is a loss of magnetic intensity by migmatization and granitization. In turn, it is known that the size of the magnetic mineral may influence the magnitude of magnetization by up to one order of magnitude (e.g., Grant 1985; Isles and Rankin 2013). Additionally, grain growth can occur by hydrothermal and metasomatic alterations (Isles and Rankin 2013). Due to the fact that the Archean nuclei of the Borborema Province were deformed and metamorphosed in the Brasiliano/Pan-African Orogeny, we may assume that the magnetic characteristics currently observed in mafic/ultramafic rocks, iron formations, and gneiss-migmatite complexes are likely the joint result of their primary characteristics and the metamorphism and deformation in the orogeny. In addition, it is necessary to consider that the Archean nuclei in the Borborema Province are affected by extensive regional shear zones. The shear deformation that affected these nuclei produced a stretched geometry, common to this tectono-structural environment, in which one of the dimensions of a body is much lower than the others, resulting in the concentration of increased magnetic susceptibility along lineaments (Figure 3). Finally, the fact that some nuclei have low total magnetic gradients, especially when the main lithological components are felsic intrusive suites, is in accordance with the magnetic characteristics of some Archean nuclei located in other large cratons (e.g., Raganai 2012; Ramotoroko et al. 2016).

6.3. Gravity signatures of the Archean units and their sources

All Archean nuclei of the Borborema Province exhibit positive residual Bouguer gravity anomalies (Figure 6E). The highest amplitudes along the profiles occur over the São José do Campestre, Troia-Pedra Branca, Alto Moxotó and Granjeiro I nuclei (20, 18, 15 and 14 mGal, respectively), whereas the lowest amplitudes relate to the Granjeiro II, Campo Grande, Itabaiana-Simão Dias and Entremontes nuclei (7, 6, 5 and 2 mGal, respectively). Considering all nuclei, the residual Bouguer anomaly of the Archean units is 5 mGal higher than that of the Proterozoic terranes (Figure 6E). This general trend is not easily explained, because Archean nuclei are predominantly formed from orthoderived rocks and large volumes of migmatized rocks, which do not seem to be the sources of these positive gravity anomalies (see, for example, the density profile across a migmatitic dome shown in figure 7 of Domingos et al. 2020). In addition, evidence for high pressure and high temperature metamorphism (granulite facies) that may favor an increase in rock density (e.g., Bourne et al. 1993) is rare in the Borborema Province. However, some nuclei have significant volumes of mafic-ultramafic rocks and iron formations, which could be sources of positive gravity anomalies. The Granjeiro II nucleus contains a long belt of iron formations that occurs in a region marked by negative gravity anomalies (BIF in Figure 11C and Profile I-J in Figure 11E). Therefore, although the presence of a residual positive residual Bouguer gravity anomaly is a persistent feature of all Archean nuclei in the Borborema Province, a simple and unified explanation for this pattern is still lacking.

In all Archean nuclei of the Borborema Province, the positive residual Bouguer gravity anomalies extend beyond the mapped Archean terranes. Based on these considerations, we raise the two following explanations for the source of positive gravity anomalies, which are not mutually exclusive. First, at positive residual anomaly does not only indicate the occurrence of Archean rocks but also a complex of rocks that also includes Paleoproterozoic units; second, the surface limits of the Archean rocks do not reflect their subsurface distributions.

Models for Archean lithospheres predict thin crust (e.g., Durrheim and Mooney 1991), as compared to Proterozoic crust, and thick lithospheric mantle (e.g., Djomani et al. 2001; Artemieva and Mooney 2002). In Brazil, thickness estimates show that the cratons have a thicker crust than the crust of Neoproterozoic fold belts (Assumpção et al. 2013). However, the available geophysical data are still not capable of distinguishing differences in thickness between Archean and Proterozoic crust in the interior of cratons. In the Borborema Province, a deep refraction seismic profile of N-S orientations allowed inferring a relatively thicker crust (~42 km) for the Alto Moxotó Domain (Soares et al. 2011). Magnetotellurics data also indicated that the Alto Moxotó nucleus has an electrically more resistive lithosphere (Santos et al. 2014) than the other Precambrian terranes crossed by the profile. In the BODES Experiment (Garcia et al. 2019), a N-S magnetotelluric profile clearly distinguishes electrically resistive anomalies in the regions of the Granjeiro I, Granjeiro II and Troia-Pedra Branca nuclei (see figure 6 in Garcia et al. 2019). However, in all these cases, both Archean and Paleoproterozoic rocks produced similar geoelectric signals, so that it was not possible to separate individual signatures for Archean and Proterozoic terranes.

In Archean terranes of large cratons, positive gravity anomalies are generally associated with iron formations and mafic/ultramafic magmatism, and negative anomalies with felsic intrusive suites (e.g., Peschler et al. 2004; Gwavava and Raganai, 2009; Ramotoroko et al. 2016; Matos et al. 2022). As discussed above for the Borborema Province, irrespective of what the dominant lithological composition may be, all Archean nuclei show positive gravity residual anomalies (Figure 6E). Moreover, in the Borborema Archean nuclei, occurrences of Neoproterozoic granitic intrusions are rare, contrary to Paleoproterozoic rock complexes and Neoproterozoic metasedimentary belts, where felsic intrusions are abundant. As the granitoids are less dense than their host rocks, the presence of granitoids decreases the density of the crust as a whole. A comparison between the geological map (Figure 1) and the gravity map (Figure 4) reveals that, as a rule, there is a correlation between occurrences of Brazilian-age granites and negative gravity anomalies. This aspect is most striking with regard to Tamboril-Santa Quitéria (TSQ in Figures 1 and 4), Águas Belas-Canindé (ABC in Figures 1 and 4), and Arcoverde-Caruaru (AC in Figures 1 and 4) batholiths.

We therefore interpret that the persistent positive gravity signature of the Borborema Archean nuclei (Figure 6E) could be due to the partial conservation of primary petrophysical characteristics of the rocks. In particular, the non-decrease in the density of the rocks in the interior of the nuclei is due to their preservation in the Brasiliano/Pan-African orogeny from the voluminous felsic magmatism that occurred in the remainder of the Borborema Province.

7. Conclusions

The Archean nuclei of the Borborema Province were investigated by analysis of gamma-ray spectrometric, magnetic and gravity data, with the aim of identifying geophysical signatures that would distinguish Archean terranes from Proterozoic units. Statistical methods were applied for numerical comparison between the signatures of the nuclei in comparison to those of the Proterozoic assemblages. The results illustrate that the Archean units indeed have distinct geophysical signatures, compared to those of the Proterozoic rocks.

Gamma-ray spectrometric data reveal that Archean rocks, generally indicate enrichment of eTh in comparison with K and eU. This relative enrichment is interpreted to be due to the fact that Th isotopes have a longer half-life than K and U isotopes and that 4.56 Ga have elapsed since the Earth's formation. Nonetheless, it was not possible to characterize a specific and individual geophysical signature for the studied Archean nuclei, due to the variety of Archean rocks found in the nuclei, which include granites, granodiorites, mafic-ultramafic rocks, and iron formations, all of different degrees of deformation.

Magnetic data show that most Archean units have higher total magnetic gradients than the Proterozoic terrane. However, the occurrence of rocks with high magnetization is not a persistent feature in all Archean nuclei. In some cases, as in the Troia-Pedra Branca and Campo Grande nuclei, weak total magnetic gradients occur. These results indicate that the current magnetic characteristics observed in mafic/ultramafic rocks, iron formations, and gneiss-migmatite complexes in Archean nuclei may well be a combined effect of their respective primary properties and later influences due to metamorphism and deformation in the Brasiliano/Pan-African Orogeny.

All Archean nuclei in the Borborema Province are characterized by a positive residual Bouguer gravity anomaly. This persistent signature is due to the partial conservation of the density distribution of the Archean lithosphere, in particular its preservation from the intense granite magmatism that occurred in the Brasiliano/Pan-African Orogeny.

Last but not least, as magnetic and gravity methods can investigate crust to depth, it has become possible to speculate about the continuity of some nuclei beyond the limits established by surface geological and geochronological data. The described geophysical signatures determined in this work may, in the future, become useful to identify hitherto unknown Archean crust in the Borborema Province.

Authorship credits

Author	A	B	C	D	E	F
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A - Study design/Conceptualization; B - Investigation/Data acquisition; C - Data Interpretation/Validation; D – Writing; E - Review/Editing; F - Supervision/Project administration.

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