Journal of the Geological Survey of Brazil vol 7, n1, 1 - 18, April 2024

Journal of the Geological Survey of Brazil

Investigation of Archean gamma-ray fingerprint: Methodology and tectonic application in central Brazil

Marcus Flavio Nogueira Chiarini[1*], Loiane Gomes de Moraes[1], Elton Luiz Dantas[2], Reinhardt Adolfo Fuck[2], Elias Martins Guerra Prado[1], Raphael Teixeira Corrêa[1], Jaime Estevão Scandolara[1,3], Antônio Augusto Soares Frasca[4], Joseneusa Brilhante Rodrigues[1], Andre Menezes Saboia[1]

[1]CPRM – Serviço Geológico do Brasil, Brasília, SEDE. SBN Quadra 02 Bloco H 2º andar, Edifício Central Brasília, Brasília-DF, CEP: 70.040-000
[2]UnB – Universidade de Brasília – Instituto de Geociências, Campus Universitário Darcy Ribeiro ICC – Ala Central, Brasília-DF, CEP: 70.910-900
[3]Present address: Amazonian Geological Agency (AGA), Rua La Plata 670, Jardim Botânico, Porto Alegre-RS, CEP: 90670-040
[4]CPRM – Serviço Geológico do Brasil, SUREG-GO, Rua 148, nº 485, Setor Marista, Goiânia-GO, CEP: 74.170-110

Abstract

Gamma-ray spectrometric responses of Archean rocks were studied in order to define a characteristic signature for these rocks. As the half-life of the most frequent Thorium isotope (^{232}Th – half life of 14.05 Ga) is more than 3 times longer relative to the Uranium isotope (^{238}U – half life of 4.50 Ga), a low response of radiation intensity in the spectral range of decay series of Uranium relative to that of Thorium is expected for Archean rocks. Based on this theoretical aspect, associated with gamma-ray spectrometric responses parametrically studied in several Archean areas of Brazil, gamma-ray and magnetometric structural interpretation, follow-up field studies, micropetrography, lithogeochemistry, and geochronology (U-Pb in zircon), it was possible to define and identify previously unidentified Archean rocks (2.82 Ga) tectonically imbricated amid Neoproterozoic magmatic arc terrains. This discovery has geotectonic implications regarding the magnitude of the Transbrasiliano Lineamento and its potential to fragment large Archean blocks and arrange them aligned within the Tocantins Province, Central Brazil.

Article Information

Publication type: Research Papers
Received 3 October 2023
Accepted 13 December 2023
Online pub. 8 January 2024
Editor: Martin Roddaz

Keywords:
Archean,
Gamma-ray spectrometry,
Transbrasiliano Lineament,
Goiás State,
U-Pb,
Uranium

*Corresponding author
Marcus Flavio Nogueira Chiarini
E-mail address: marcus.chiarini@sgb.gov.br

1. Introduction

The Archean eon comprises the time between 4.0 to 2.5 Ga. Although it corresponds to one third of Earth's history, its rock record represents less than 5 % of the presently exposed continental crust (Benn et al. 2006). Finding more of these rocks is essential to constrain geodynamic models of mantle heat distribution, and consequently the early formation, stabilization and preservation of continents.

Turcotte and Schubert (2014) show that the earth's internal heat production was 2-3 times larger in the Archean. Radioactive heat-producing isotopes of Uranium (U), Thorium (Th) and Potassium (K) are responsible for the main generation of heat within the crust and mantle (Figure 1). K and U contributed more during the Archean due to smaller half-lives $t_{1/2}$ while Th contribution was nearly constant over time.

Excluding surface processes, the radiometric signature of a rock is the result of its initial concentration of K, Th and U less the amount lost due to radioactive decay. For instance, the radiation/heat of an Archean rock emitted in the U channel today is approximately three times smaller than when it was formed, while for the Th channel the radiation emitted practically did not change (Figure 1).

The most common plutonic suite in Archean terrains is Tonalite-Trondjhemite-Granodiorite (TTG). Initially it was thought to be limited to the Archean, however it also occurs in younger systems. According to Condie (2016) and references therein, TTGs composition is similar regardless of age. Therefore, assuming the composition of plutonic rocks with TTG signature is similar during their formation and that the content of U and K will decrease faster with time than that of Th, we test if airborne gamma ray spectrometry can distinguish Archean TTGs from non-Archean TTGs. Consequently, we

ISSN: 2595-1939
https://doi.org/10.29396/jgsb.2024.v7.n1.1
Open access at https://jgsb.sgb.gov.br/index.php/journal

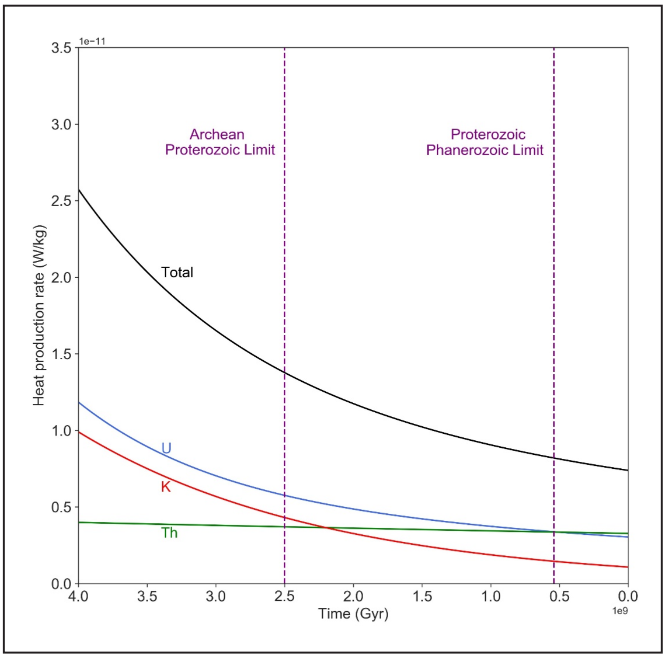

FIGURE 1. Difference in heat flow over time for radioactive elements. The graph shows the radiogenic heat emitted by K and U and Th decay series on the vertical axis. The horizontal axis shows the time (Earth Age) from 4.0 Ga onwards highlighting the decay curve of the U series in relation to that of Th, which for this time scale is shown as an almost straight line, since the half-life of ^{232}Th is three times larger (modified from Turcote and Schubert, 2014).

test if this hypothesis is valid to identify new Archean terrains as inliers in rocks formed during Neoproterozoic accretion and collision processes, as well as their implication in the tectonic evolution of the Tocantins Province and in the understanding of the Transbrasiliano Lineament.

2. Conceptual basis - Thorium and uranium radioactive elements

U and Th are classified as high-field-strength elements, thereby sharing similar chemical properties such as charge over ionic radius and valences (Table 1). U has atomic mass equal to 238 and atomic number equal to 92 and is the last natural chemical element in the periodic table, whereas Th has atomic mass and atomic number equal to 230 and 90, respectively (Albarède 2009).

Only two isotopes of U are found naturally in the crust: ^{238}U and ^{235}U. ^{238}U is the dominant isotope representing about 99.275% of all natural U, therefore, we only consider ^{238}U for this study. On the other hand, ^{232}Th is the only naturally occurring isotope of Th. Despite of several commonalities, the half-life of these elements differs substantially. The half-life of ^{238}U is about 4.50 Ga while the half-life of Th is three times higher: 14.05 Ga (Dentith and Mudge 2014; Turcotte and Schubert 2014).

TABLE 1. Physico-chemical properties of Th and U. (Compiled from Albarède 2009).

Physico-chemical Properties	Th	U
Atomic Number	90	92
Mass Number (more stable isotope)	232 (100 %)	238 (99.2742%)
Atomic Radius	180pm	179 pm
Periodic Table Family	Actinide	Actinide
Most Common Isotope	232Th	238U (99.2742%)
Oxidation Number	+4 (+3.+2)	+3,+4,+5,+6
Most Common Isotope Half-life	**~14,05 Ga**	**~4,50 Ga**

U and Th are actinides with physico-chemical similarities and for this reason they tend to occur, mostly, with a positive correlation in plutonic rocks, which are conducted, in their genesis, by the laws of thermodynamics. The positive correlation between U and Th is valid for igneous rocks, but not for sedimentary rocks that have their genesis controlled by other factors.

Assuming U and Th are immobile in magmatic systems (Jiang et al. 2005), the half-life difference between U and Th is the reason why the emission intensities in the U and Th power spectrums do not remain constant over time (Turcote and Schubert 2014). The ratio of Th to U is nearly constant in the crust, however the relative loss of U compared to Th due to time may affect this relation. Therefore, the older the rock, the greater this difference.

3. Empirical observations - Gamma-ray Spectrometric signatures of Archean rocks

A similarity of gamma-ray spectrometry signatures related to Archean rocks is observed. This signature is shown in the images below (Figures 2, 3, and 4), in which the shades of yellow color (merging with shades of red and green) refer to low concentration of Uranium when compared to Thorium and Potassium concentrations. Figures 3 and 4 show a low Uranium signature relative to Potassium and Thorium patterns.

4. Data and methods

Airborne gamma-ray spectrometry high resolution data were used in empirical studies in relation to the concentration of Thorium and Uranium and their relative behaviors. We used the compilation of Correa (2019), called the Radiometric Map of Brazil. It is composed of 112 airborne projects with

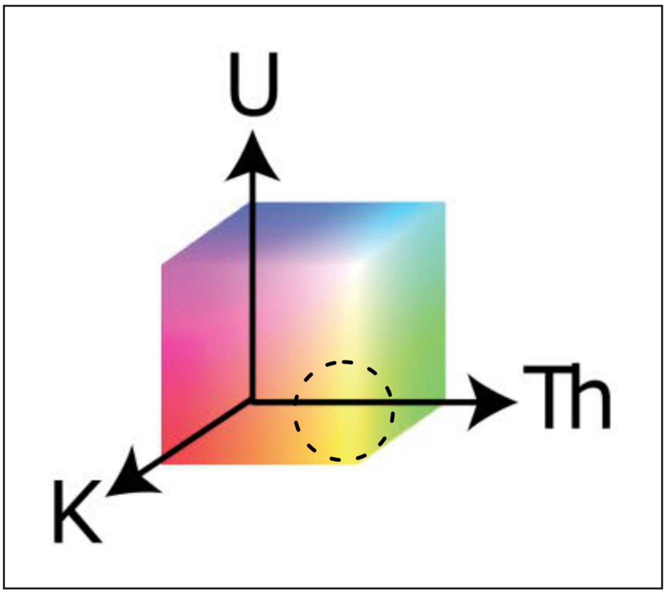

FIGURE 2. Domain close to the K-eTh edge, opposite the Uranium vertex, (very low Uranium content).

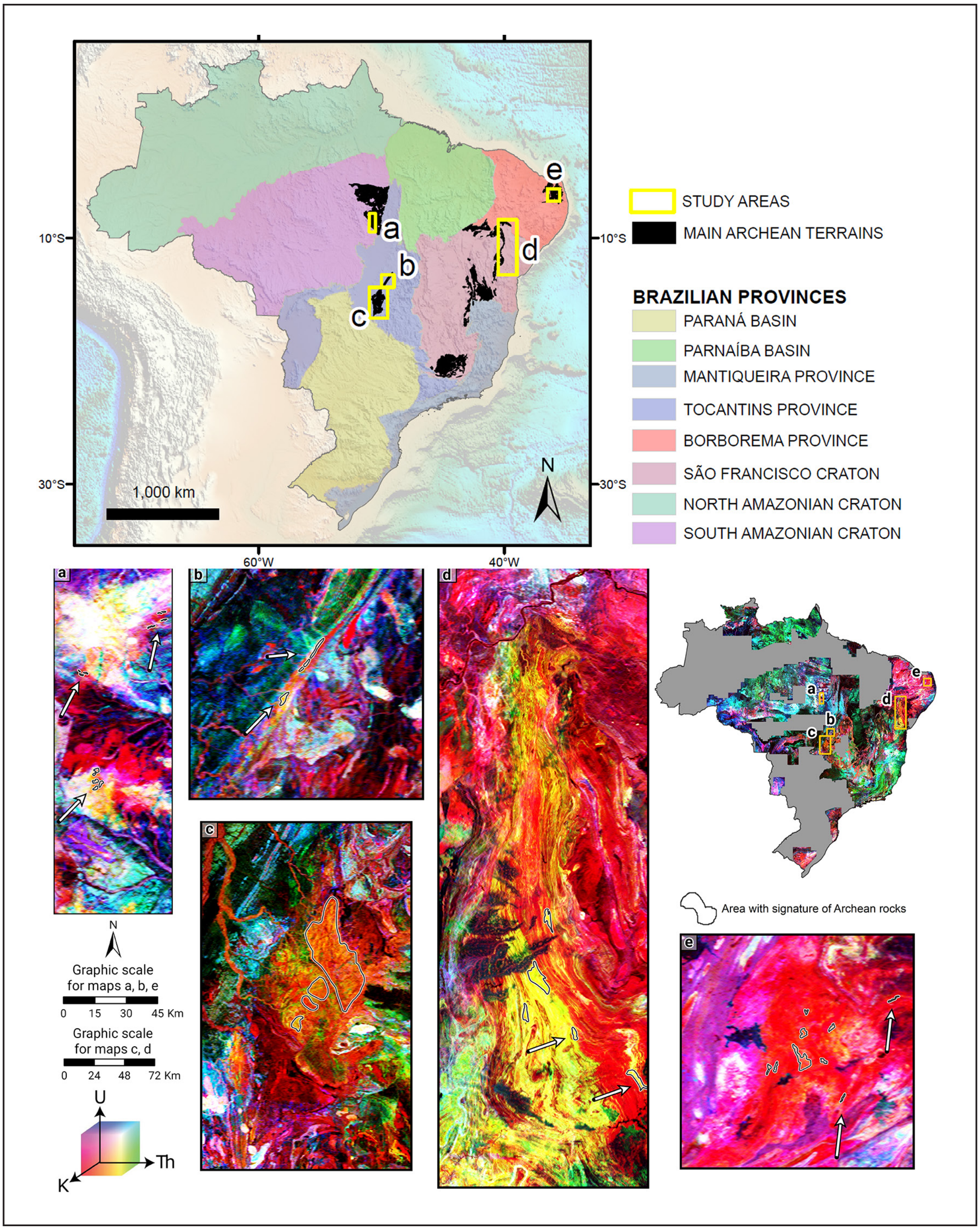

FIGURE 3. Gamma-ray spectrometric signature of several regions of Brazil. Shades of yellow colour are related to Archean rocks. Dashed areas show Archean rocks gamma-ray spectrometry signatures. A - Rio Maria Archean Domain, B - Serra Azul Archean Complex, C - Archean Goiás Block, D - São Francisco Craton, E - Borborema province, São José do Campestre. Modified from Correa et al. (2019) and Tapias et al. (2019).

flight height of 100 m and flight line spacing of 500 m. The grids of Potassium, equivalents of Thorium and equivalents of Uranium were interpolated with 125 m cell size. Each element was normalized using the superposition area between projects in a least square sense.

The eTh/eU ratio derived from gamma-ray spectrometric data of regions with Archean age dated rocks was used as a reference for the attempt to identify similar rocks that have not yet been mapped.

Field analysis (follow-up) and rock sampling were carried out in areas that presented eTh/eU ratios similar to those already mapped as Archean, in order to perform lithochemical analysis, to compare the geophysical signal with analogous areas and to guide geochronological sampling. The Neoproterozoic Goiás Magmatic Arc was chosen as the investigation area for this study, given that it includes patches with a gamma-ray spectrometric signature analogous to other terrains already known to be of Archean age and, therefore,

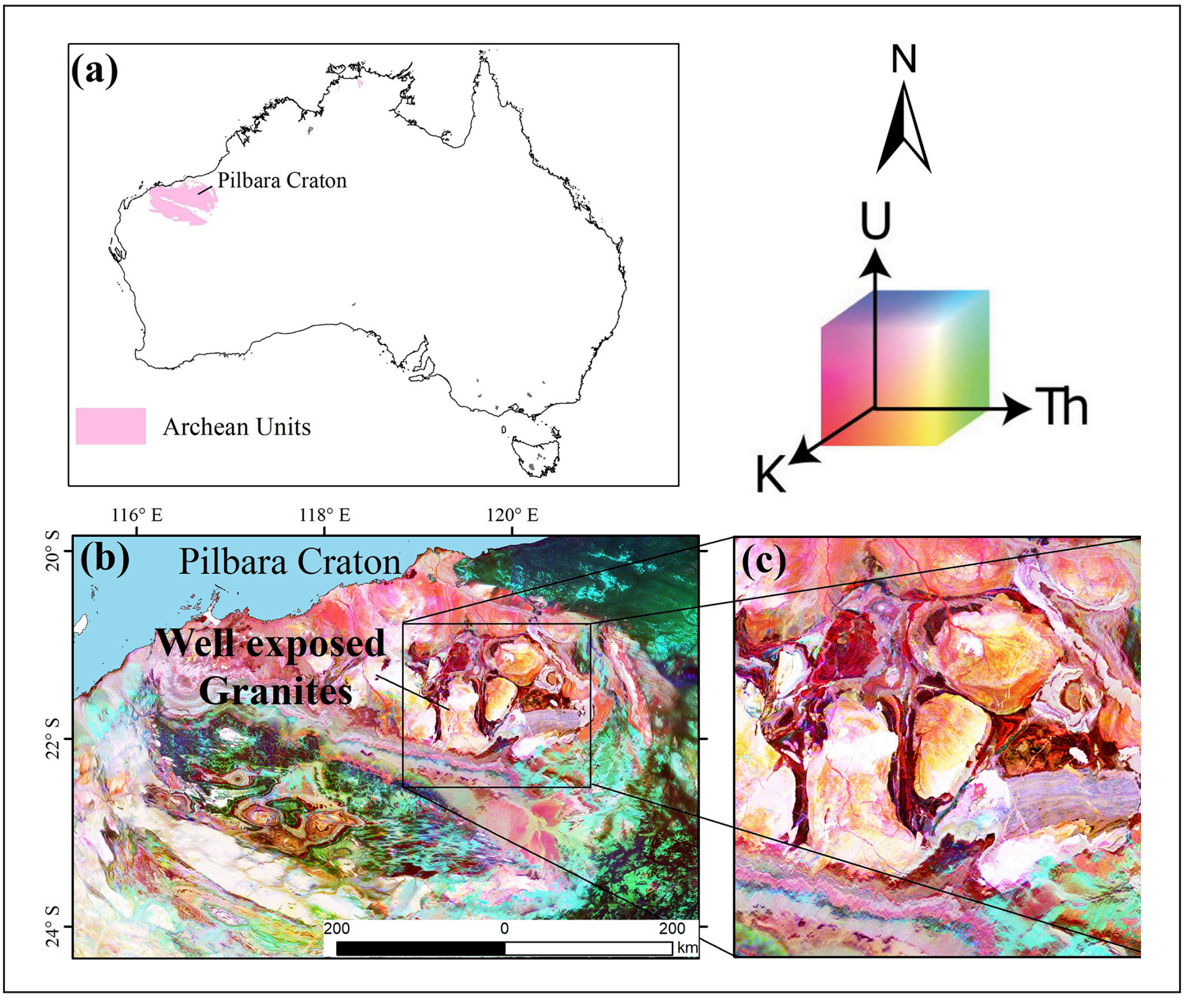

FIGURE 4. Pilbara Archean Craton in Australia and its gamma-ray spectrometric signatures.

with the potential to be older than what is currently known and mapped as of Neoproterozoic age.

In situ zircon U-Pb LA-HR-ICP-MS analysis were undertaken at the Laboratório de Estudos Geocronológicos, Geodinâmicos e Ambientais of the Universidade de Brasília (UnB), Brasília, Brazil. The analysis followed procedures described in detail in Bühn et al. (2009). Heavy minerals were obtained by crushing the rock, sieving and panning. The heavy minerals passed through the Frantz isodynamic separator and from the non-magnetic fraction, zircon crystals were hand-picked under a binocular microscope. The selected grains were mounted in epoxy resin, abraded and polished with diamond paste. Analysis were preceded by backscattered electron (BSE) imagery, also done at UnB using a Scanning Electron Microscope (SEM), FEI Quanta 450. The analysss were performed with a Thermo Finnigan Neptune multicollector inductively coupled plasma mass spectrometer with an attached New Wave 213µm Nd-YAG solid state laser. The acquisition followed a standard – sample bracketing technique with eight sample analysis between a blank and a GJ-1 zircon standard. The accuracy was controlled using the zircon standard 91500. Raw data were reduced using an in-house program (Chronus, Oliveira 2015) and corrections were done for background, instrumental mass-bias drift and common Pb, as described in Bühn et al. (2009). The ages were calculated using ISOPLOT 4.15 (Ludwig 2012). Data with analytical errors and common lead greater than 3.5% and 3%, respectively, were not used in the age calculations.

Major element analysis was carried out by X-ray fluorescence (XRF) at the SGS GEOSOL laboratory in Vespasiano, Minas Gerais (Brazil), according to its pre-established XRF79C analytical method. The rock powder (~2 grams per sample) was dried in an oven and weighed after cooling in a jar containing lithium tetraborate flux. The sample was then transferred to a platinum crucible and homogenized. After homogenization, lithium iodide was added before fusion in an automatic machine and analyzed by XRF. Trace element analysis were carried out by inductively coupled plasma mass spectrometry (ICP-MS) at the SGS GEOSOL laboratory in Vespasiano, Minas Gerais (Brazil), according to its pre-established IMS95A analytical method. The rock powder (~10 grams per sample) was weighed and fused in a graphite crucible by adding lithium metaborate. After fusion, the melt was transferred to a beaker containing a solution of nitric acid and tartaric acid in equal volumes before homogenization and total dissolution under agitation and analysis of the solutions by ICP-MS.

5. Results

After an empirical analysis of the gamma-spectrometric data, we observed that the Archean and Paleoproterozoic rocks present a specific pattern of emission of gamma-rays in some studied areas, mainly due to the relative low concentration of Uranium. This peculiar geophysical signature motivated us to a further study the gamma-ray spectrometric signature of Precambrian rocks.

Other data, such as structural geology, lithochemistry and geochronology, were obtained to increase efficiency and support the results.

The eU vs eTh graph (Figure 5) shows the linear regression of fitted and adjusted data of the cluster distinguished by age. The gamma-ray spectrometric data for the eU channel are represented in the vertical axis, the eTh channel data are shown in the horizontal axis. Points plotted by age and line adjusting for each age were done using all the database of the Geological Survey of Brazil - SGB / CPRM (242,398,387 pixel samples). Airborne gamma-ray spectrometric data points previously discriminated as belonging or not to mapped Archean and non-Archean rocks polygons were used. We observed that for the array of points belonging to the Archean rocks, the adjusted line has the lowest angular coefficient, meaning that even for high eTh contents, eU is relatively low. In addition, it is possible to observe the significant lack of high concentrations of eU in Archean rocks.

As an additional consideration, it is possible to distinguish several trends in the Graph (Figure 5) that justify detailed studies about the genesis and their cluster following a constant ratio between Uranium and Thorium. Studies of which geological reasons for this behavior of classes with the same angular coefficient may be required. We only addressed the trend of data discriminated as Archean by the proposed sampling polygons selected as known Archean.

Figure 6 shows the boxplot statistics of the values of eTh, eU and K.

We notice that the average values of Potassium and Thorium are higher for the areas selected as Archean. The average of the eU values in the Archean pixels areas is less than the average in the other pixels areas. This shows a distinct behavior for Uranium for that signature specifically,

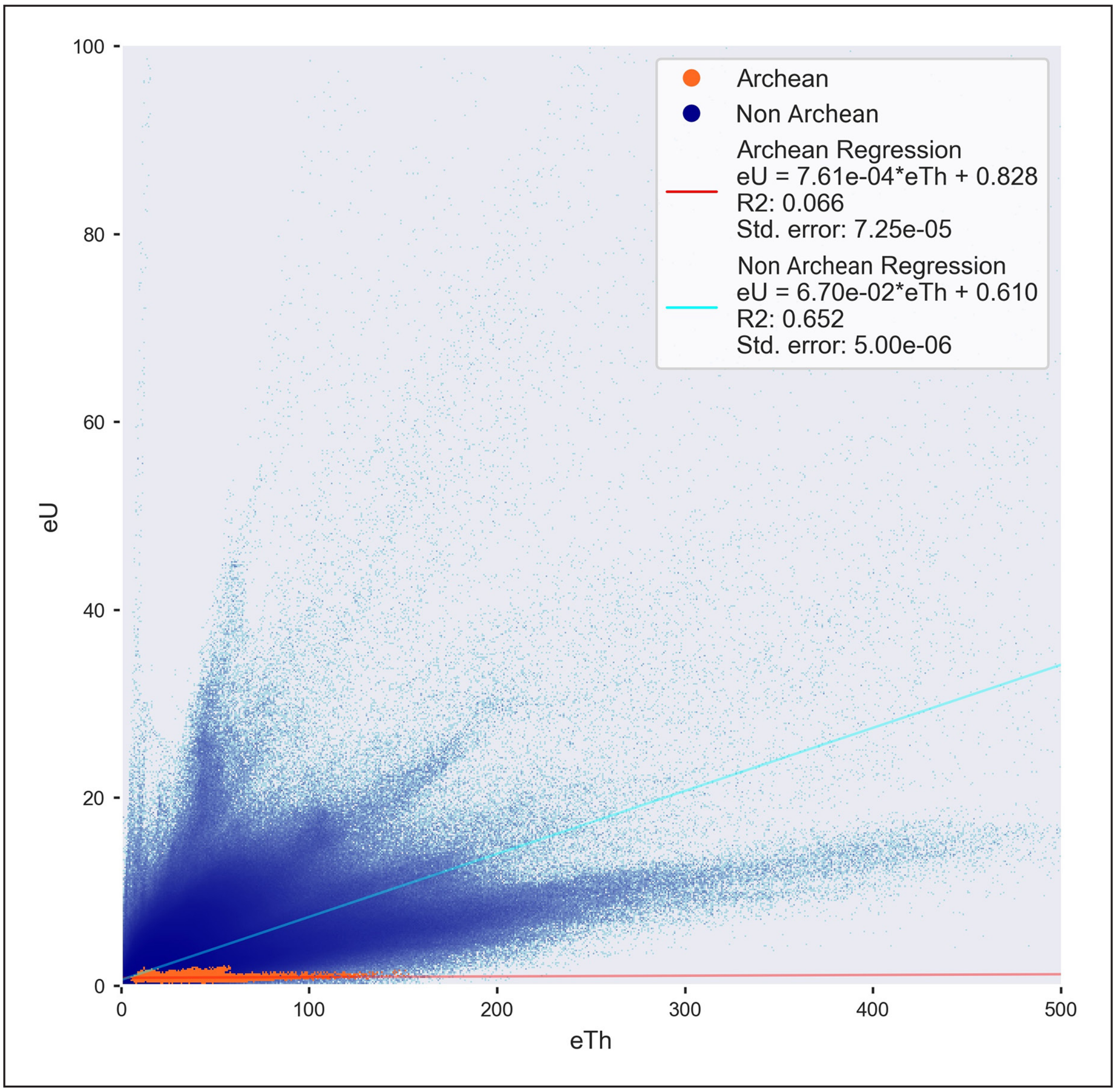

FIGURE 5. Graph of eTh vs eU concentrations from gamma-ray spectrometric data. The lines show the linear regression between these two variables for pixels located in areas of Archean age (orange) and for pixels located in others areas non-Archean (blue). Note an adjustment line for Archean rocks with the lowest angular coefficient in relation to the line obtained for non-Archean rocks. Particularly, even for high eTh contents, the eU contents are low in Archean rocks, describing an almost orthogonal independence.

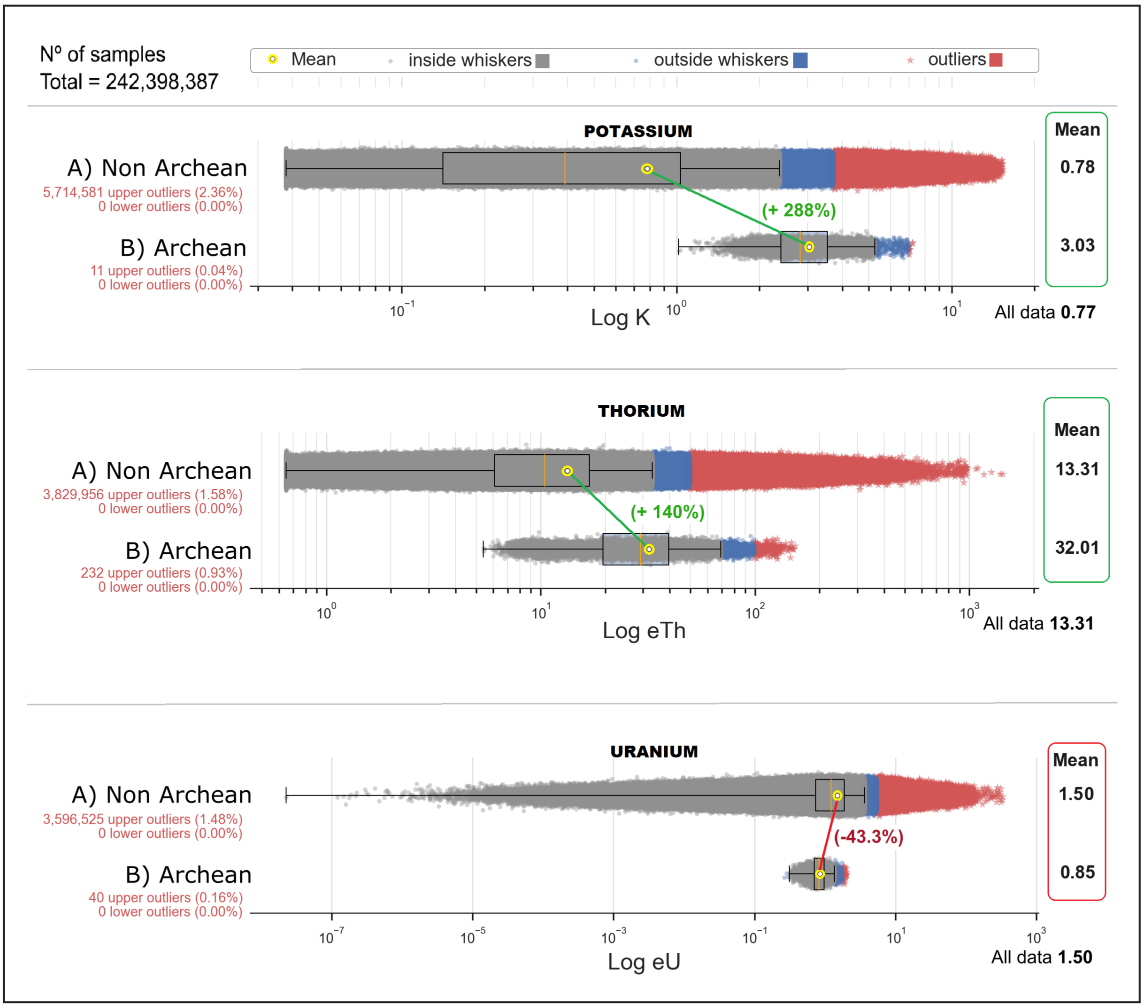

FIGURE 6. Boxplot statistics of eTh, eU and K values from gamma-ray spectrometric data. A) corresponds to the statistics obtained for the entire gamma-spectrometric data set in Brazil, except for pixels located in Archean regions; B) corresponds to the statistics obtained for the pixels inserted in the selected polygons as having a signature potentially related to Archean rocks.

in contrast to its physico-chemical similar element Thorium, which presents the opposite behavior.

We observed that the average concentrations of Potassium in Archean rocks are higher than those for non-Archean rocks, and in the case of TTG (Tonalite-Trondhjemite-Granodiorite), sanukitoids and even granites (subordinate greenstone belts in much smaller volume) present higher Potassium contents in relation to the whole group of sampled non-Archean rocks (the entire gamma-ray spectrometric data set of Brazil, that includes sedimentary and metasedimentary rocks areas with low radiogenic content, contributing to these average in the general statistics). The same is observed in relation to eTh: when the data of the Archean rocks are separated, they show a higher concentration than the non-Archean rocks. Even having usually a positive correlation for K, Th, and U, in observing the radiation statistics for the U series, the opposite of the behavior in relation to Th is seen. Positive correlation between K, Th, and U is naturally expected, mainly between K and Th, which have very similar physico-chemical properties. Lower radiometric values are observed for Uranium in Archean rocks. Due to the higher decay rate, the production of radiogenic heat by Uranium was greater in the Archean and decreases over time in half-life ratio much more quickly in relation to the production of radiogenic heat by Thorium, which remains practically constant over time. As observed in the graph in Figure 1, the curve of radiation emitted by the Uranium spectal channel shows a greater decay in relation to time compared to Thorium. Thus, for Archean rocks, the radioactive daughter elements of the Uranium series are in the crystalline structure with smaller gamma-ray spectometric emission in this spectral range. The same does not occur with Thorium, which remains almost constant. this difference can be observed by this geophysical method of aerogamaspectrometry as an indirect indicator for tracking archean rocks. On the other hand, it is important to attempt to the large variety of Archean rocks and different ratios between Thorium and Uranium among these rocks. A specific accurate subscription is not possible for this tracker. Therefore, the need to work with more tools (structural, geochemical and observing the gamma-ray spectrometric signatures of Archean rocks close to the area to be studied).

Within the entire set of gamma-ray spectrometric data from Brazil, polygons that cover areas already known as Archean were selected to be statistically compared in relation to the data set outside these polygons. Regarding

Potassium contents, the non-Archean group presented an average of 288% in relation to Potassium within the Archean polygons. For Thorium, the gamma-ray spectrometric equivalent contents were 140% higher for non-Archean areas. As for the radiation equivalent contents for the Uranium decay series, we observe the opposite behavior to Potassium and Thorium. The averages were 43% lower in the areas selected as known as Archean in relation to the non-Archean data set (Figure 6).

6. Study Area

The area of study (Figures 3 and 7) comprises the Neoproterozoic Goiás Magmatic Arc, located in the Tocantins Province. The test method is independent of the geographic region since it is applied in areas of Precambrian rocks and with very heterogeneous ages, where the mapping activity did not focus on detailing. Thus, an area was proposed in the Neoproterozoic Goiás Arc, namely the Arenópolis Arc and an adjacent portion related to the Archean terrains of the Goiás Massif, chosen to perform a parametric study.

6.1. Geological Setting

The Tocantins Province, central Brazil, formed during the Brasiliano orogeny, in the context of West Gondwana amalgamation involving the collision of the Amazonian, São Francisco and Paranapanema paleocontinents, and comprises a system of three orogens, namely the Brasília, Araguaia and Paraguay fold belts (Fuck et al. 2017).

The region of this research comprises two major lithostructural domains within the central portion of the Brasília Orogen (Fuck et al. 2014; Borges et al. 2021): the Crixás-Goiás domain, which is part of the Goiás Massif and the Arenópolis Magmatic Arc, the latter comprising most of the studied area.

The Goiás Massif is a continental block, exotic and allochthonous, with a long and complex crustal evolution, which collided with the western Sanfranciscan margin in the Neoproterozoic. This block is composed of six orthogneissic complexes and five low-grade metamorphized greenstone-belts of Archean and Paleoproterozoic ages. In the northern outcrop the Hidrolina, Moquém, Caimar and Anta complexes and host the Crixás, Pilar de Goiás and Guarinos greenstone-

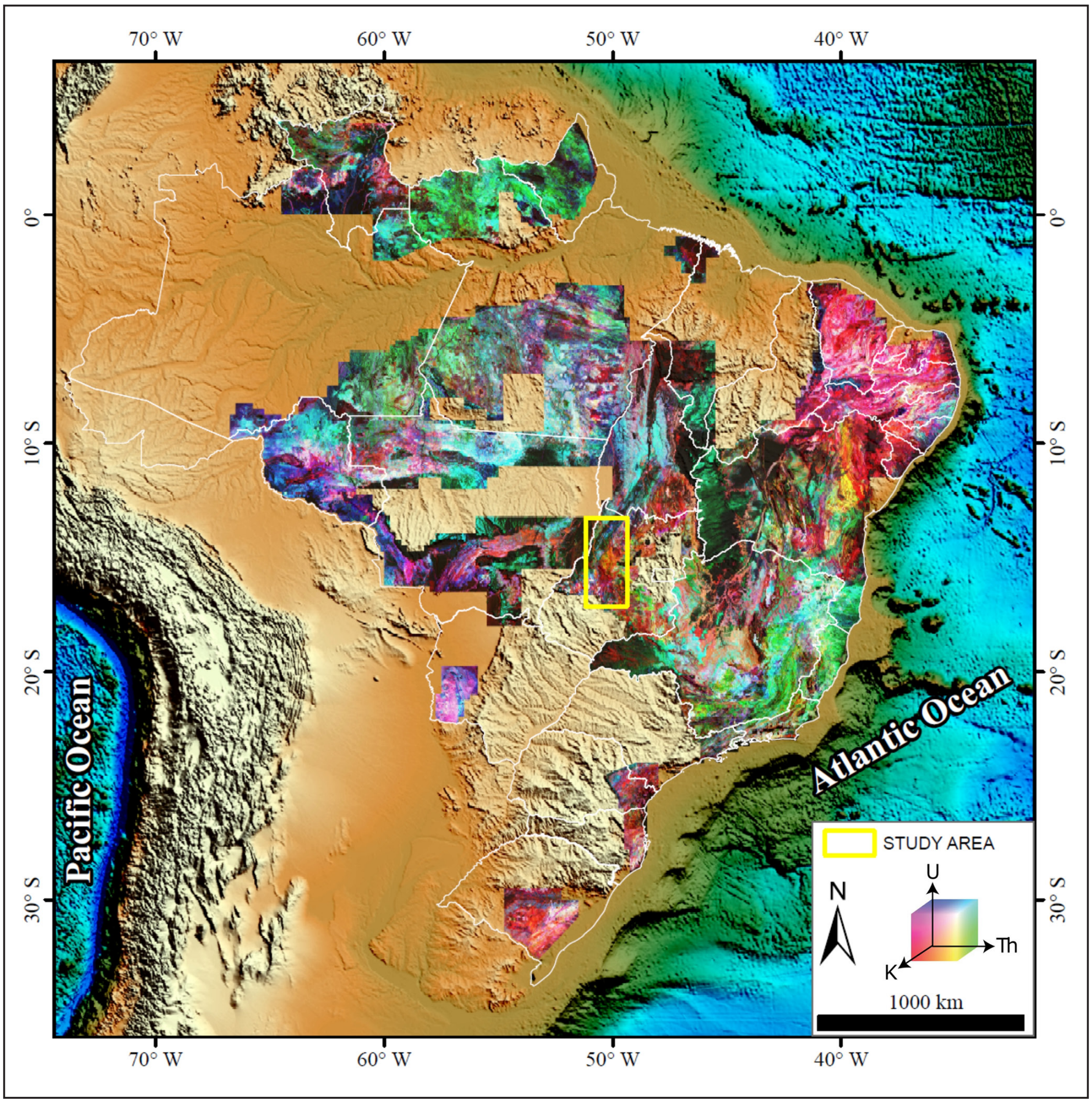

FIGURE 7. Gamma-ray dataset of Brazil and the study area location.

belts and other smaller ones. To the south are the Caiçara and Uvá complexes and the greenstone-belts of Serra de Santa Rita and Faina (Jost et al. 2013; Frasca 2015).

The Crixás-Goiás domain of Archean-Paleoproterozoic terrains is characterized by a typical association of granite-gneiss complexes and low-grade metamorphic greenstone belts (Jost et al. 2013; Borges et al. 2021). Concerning the granite-gneiss rocks, the Uvá complex is located in the southern portion of the terrane (Jost et al. 2013), and consists of ca. 3.10 to 2.93 Ga TTG (Rio do Índio domain) batholiths that are intruded by bodies of ca. 2.87 to 2.84 Ga tonalites, granodiorites and monzogranites (Rio Vermelho domain).

Complexo Uvá is an association of southern orthogneisses of the Archean terrains of Goiás and is subdivided into 2 domains. The Rio do Indio Domain is composed of dioritic, tonalitic and granodiorite gneisses aged 2.93 Ga. The Rio Vermelho Domain is formed metatonalite, metamonzonite and metagranodiorite aged 2.75 Ga. Both domains Sm-Nd dating indicate age between 3.0 Ga. and 3.2 Ga (Jost et al. 2005).

Jost et al. (2010, 2013), describe the Goiás Massif as an exotic and allochthonous terrain, amalgamated to the Tocantins Province during the final stages of the Brasiliano Orogeny. According to these authors, this massif is formed by the oldest rocks in the region, whose protoliths are TTGs, tonalites-granodiorites and polydeformed diorites with crystallization ages between 3040 Ma and 2930 Ma.

The Arenópolis Arc is the southern portion of the Neoproterozoic Goiás Magmatic Arc, which represents intraoceanic island arcs developed between ca. 0.9 to 6.3 Ga (Pimentel 2016).

The Paraná Basin, exposed to the south of the studied region, is a Paleo-Mesozoic intracratonic basin that covers the Paranapanema block in central Brazil (Hasui 2012). The Paranapanema block is a large sialic segment which is accessed by direct data from deep drilling and geochronology and traced by geophysical data (Affonso et al. 2021).

Regarding the geotectonic setting, remarkable late-collisional shear zones, such as the Transbrasiliano and Moiporá-Novo Brasil lineaments, separate the Arenópolis Arc and the Crixás-Goiás domain (Jost et al. 2013).

The investigated region occupies a key area to understand the late Neoproterozoic processes of western Gondwana assembly, particularly the evolution of orogenic belts and supercontinent reconstruction models. In particular, the Brasília Orogen is the result of a complex collisional process involving paleocontinents and smaller continental pieces with amphibolite-facies deformation and metamorphism and S-type granites around 650-630 Ma, reflecting the final closure of the Goiás-Pharusian Ocean (Pimentel 2016; Fuck et al. 2017). In addition, the original boundaries of these paleo plates were strongly modified by the continental strike-slip system of the Transbrasiliano-Kandi Lineament that crosses both South America and Africa (Cordani et al. 2016).

In this geodynamic context, expressive basement inliers and small-scale cratonic fragments have been recognized within the Brasiliano orogens, as for example, in the Tocantins and Borborema provinces (Brito Neves et al. 2021). Thus, the identification and characterization of the geophysical signature of these reworked inliers is a major issue in addressing the paleogeographic and paleotectonic context of Proterozoic orogens and supercontinents.

7. Field research, analysis, and results

The areas were selected based on gamma-ray spectrometry features for field investigation, sampling for petrography, lithogeochemistry and U-Pb geochronology of zircon (Figure 8).

The fieldwork consisted of checking and sampling outcrops (Figure 9) in the previously selected areas through interpretation of airborne gamma-ray spectrometry images as signatures of eU-eTh correlation, potentially related to Archean/Paleoproterozoic rocks. Some similar aspects in the power spectrum have been identified, such as a low radiation emission in the spectral range of the Uranium series in relation to the Potassium and Thorium series.

7.1. Petrography

Fifteen microscopic analysis of the rocks collected in the fieldwork internal areas of interest were performed, comprising metagranodiorites, metatonalites and granites previously mapped as belonging to the Neoproterozoic units of the Arenópolis Magmatic Arc. However, these samples were characterized due to their geophysical signature as potentially related to older rocks.

The following description is of the most representative sample of the group (Figure 10). It has a microstructure of a poorly developed, irregular and slightly spaced parallel protomylonitic to gneissic foliation. It is very fine- to medium-grained with an allotriomorphic, granolepidoblastic texture. The main crystal phases are xenomorphic subrounded to stretched quartz crystals with recovery microtexture and subgrains development. These newly developed quartz crystals show polygonal contacts. Feldspar crystals, both untwinned plagioclase and alkali feldspar are mainly xenomorphic, with sutured contacts. Some better preserved feldspar crystals from the dynamic deformation are tabular, subidiomorphic and are arranged parallel to the foliation. A mosaic composed of fine-grained granoblastic quartz and feldspar crystals surrounds these larger crystals. The arrangement of this mineral assemblage, together with the lamellar biotite and muscovite crystals, underlines the protomylonitic to gneissic foliation. Accessory minerals such as magnetite, apatite, allanite and zircon are usually in association or occur as inclusions in the phyllosilicates. Biotite is partially replaced by chlorite and plagioclase crystals have a cloudy appearance due to partial sericitization and weathering.

7.2. Lithochemistry

7.2.1. Major and trace element geochemistry

The three samples of tonalite and one granodiorite analyzed are representative of the set of rocks obtained by field followup and are plotted in Appendix 1, characterized by medium SiO_2 (65.9-68.20 wt.%), high Na_2O (5.36-5.53 wt.%), Al_2O_3 (16.50-16.90 wt.%), Sr/Y (37.47 and 165.48), La/Yb (36.60 and 50.67), and low K_2O/Na_2O (0.35 and 0.35), besides high Al_2O_3/TiO_2 ratio. These samples of tonalites and one granodiorite show chemical classification consistent with the petrographic observations (Figure 11a), plotting in medium-K calc-alkaline (Figure 11b), fall into the trondhjemite field in the An–Ab–Or plot (Figure 11c), and in ternary discrimination diagrams from Laurent et al. (2014) (Figure 11d) plot in the

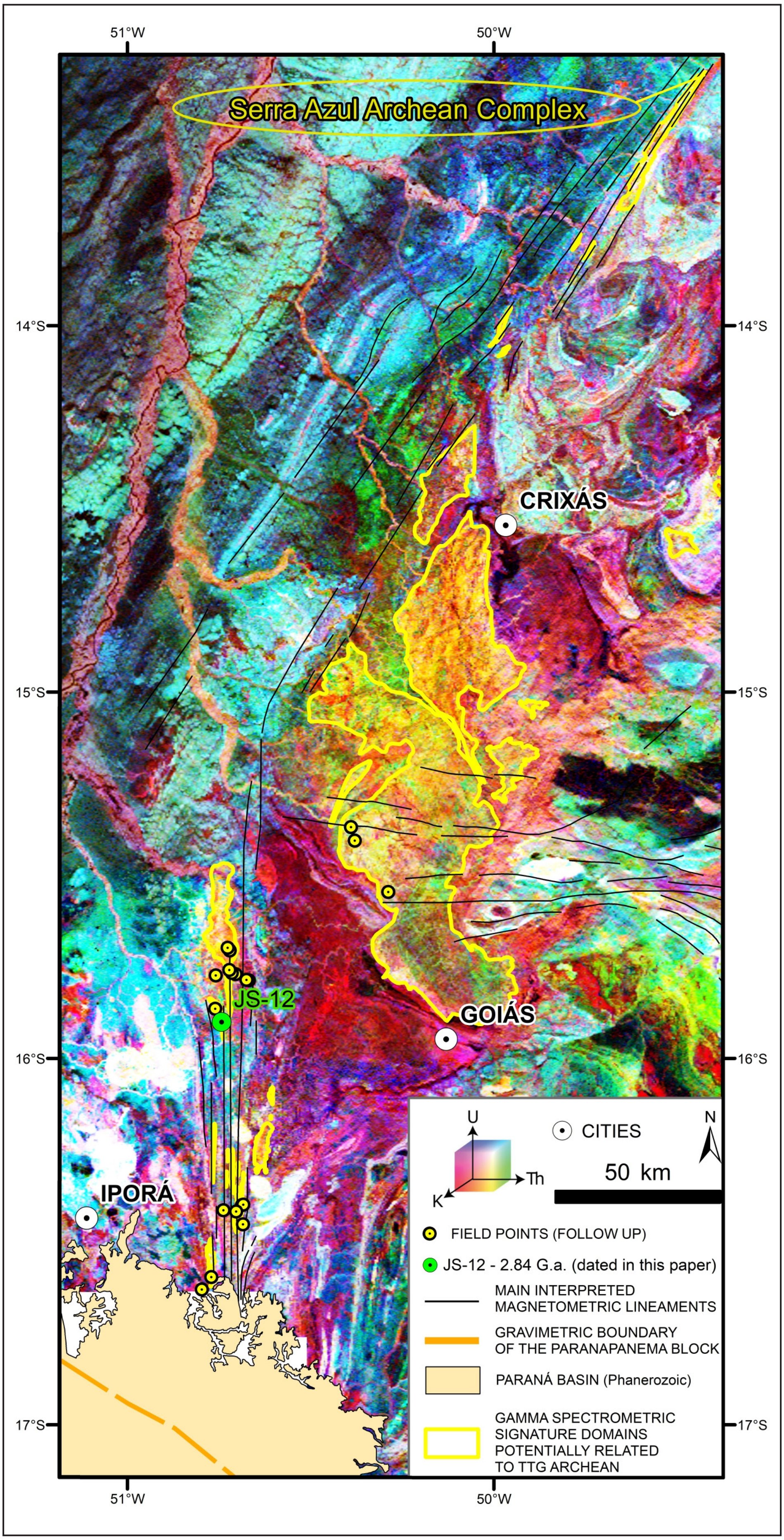

FIGURE 8. Characteristic gamma-ray spectrometric signature domains and field points checked by follow up.

FIGURE 9. Outcrop of representative biotite monzogranite identified in fieldwork by follow-up support of the gamma-ray spectrometry images.

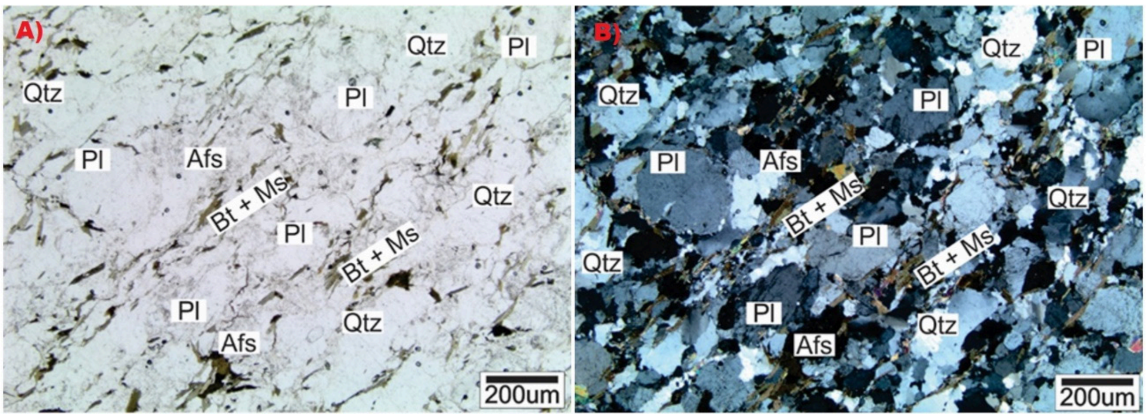

FIGURE 10. Schematic illustration of the micropetrographic analysis of sample JS-12: Tonalite. JS-12 thin section photomicrograph 20x PPL (A) and XPL (B) showing protomylonitic to gneissic structure. Qtz – Quartz, Pl – Plagioclase, Bt – Biotite, Ms – Muscovite, Afs - Alkali Feldspar.

TTG field. These rocks can be characterized as high La/Yb ratio TTGs, derived from magmas generated at intermediate to high-pressure conditions (~2.0 GPa) in the garnet stability field (Almeida et al. 2011).

In order to improve the chemical classification of the studied rocks and suggest the sources of the three tonalites, and granodiorite we compared their geochemical compositions with those of different Archean granitoid types worldwide (TTG, transitional TTG, sanukitoids, Closepet-type, and K-rich granites; data from Martin 1994; Champion and Sheraton 1997; Moyen et al. 2003) and with granite compositions corresponding to melting of various sources, as determined by experiments (e.g., Lopez et al. 2006; Figures 11a, and 11b). In the A/CNK vs. K/Na and the A/CNK vs. Mg# diagrams of Figures 12a, and 12b, the samples plot in the fields of transitional and enriched TTG, and according to experimental data (e.g., Lopez et al. 2006, and references therein) dehydration melting of tonalite will produce small melt volumes of granitic/granodioritic composition.

With low to moderate K/Na ratios and medium Mg#, the intermediate rock samples studied plot within or at least nearby the compositional field of experimental melts produced by the interaction between basic magma and tonalitic crust.

7.3. U-Pb geochronology

One sample was analyzed by the U-Pb on zircon method (JS-12).

In order to evaluate the applicability of the proposed methodology, areas (Figure 8) were selected to be studied isotopically and to check if they represent old terrains (Archean). For this purpose, sample had their U-Pb isotopic content determined by LA-HR-ICP-MS.

Sample JS-12 is a tonalite, with zircon grains occurring as 165-455 μm-long prisms with bipyramidal terminations or fragments. They present few inclusions and fractures. In BSE images, discrete and well-marked oscillatory zoning, homogenous grains and areas, as well as core and rim are observed (Figure 15). In several grains there are areas (core or intermediate rim) very rich in small inclusions, rendering a spongy aspect (e.g. crystals 16, 17 and 18), probably effects of metamictization.

Thirty-nine spots on thirty-six crystals were analyzed (Appendix 2). Almost all grains present Th/U ratios around 0.5, except for spot Z15N, with Th/U ratio of 0.08. In general, they have low contents of common lead and only three spots had their data discarded due to high analytical errors.

The obtained data indicate three age groups. The main and oldest group are from crystals with core and rich in inclusions. The spots were located both on the cores and on the rims, mostly rendering Archean ages. There is an isolated point with $^{207}Pb/^{206}Pb$ apparent age of 3269±15 Ma (zircon 15, Figure 13), interpreted as crustal contamination or inheritance. The regression of the other 24 Archean points (Figure 14) resulted in the upper and low intercepts of 2840±11 and 550±76 Ma, respectively (MSWD=2.8). The upper intercept is interpreted as the protolith crystallization age.

The second group is represented by crystals with few inclusions and discrete oscillatory zoning (e.g. crystals 3, 5, 9). The regression of eight points indicates the upper intercept of 2088 ± 27 Ma and lead loss of 432 ± 250 Ma (MSWD of 0.21). The upper intercept possibly indicates the age of the deformational event that generated the gneiss.

Two spots with Neoproterozoic ages were identified ($^{206}Pb/^{238}U$ apparent ages of 540 Ma and 506 Ma). Both crystals and the lower intercepts of the regressions indicate that this rock was affected by a Neoproterozoic event.

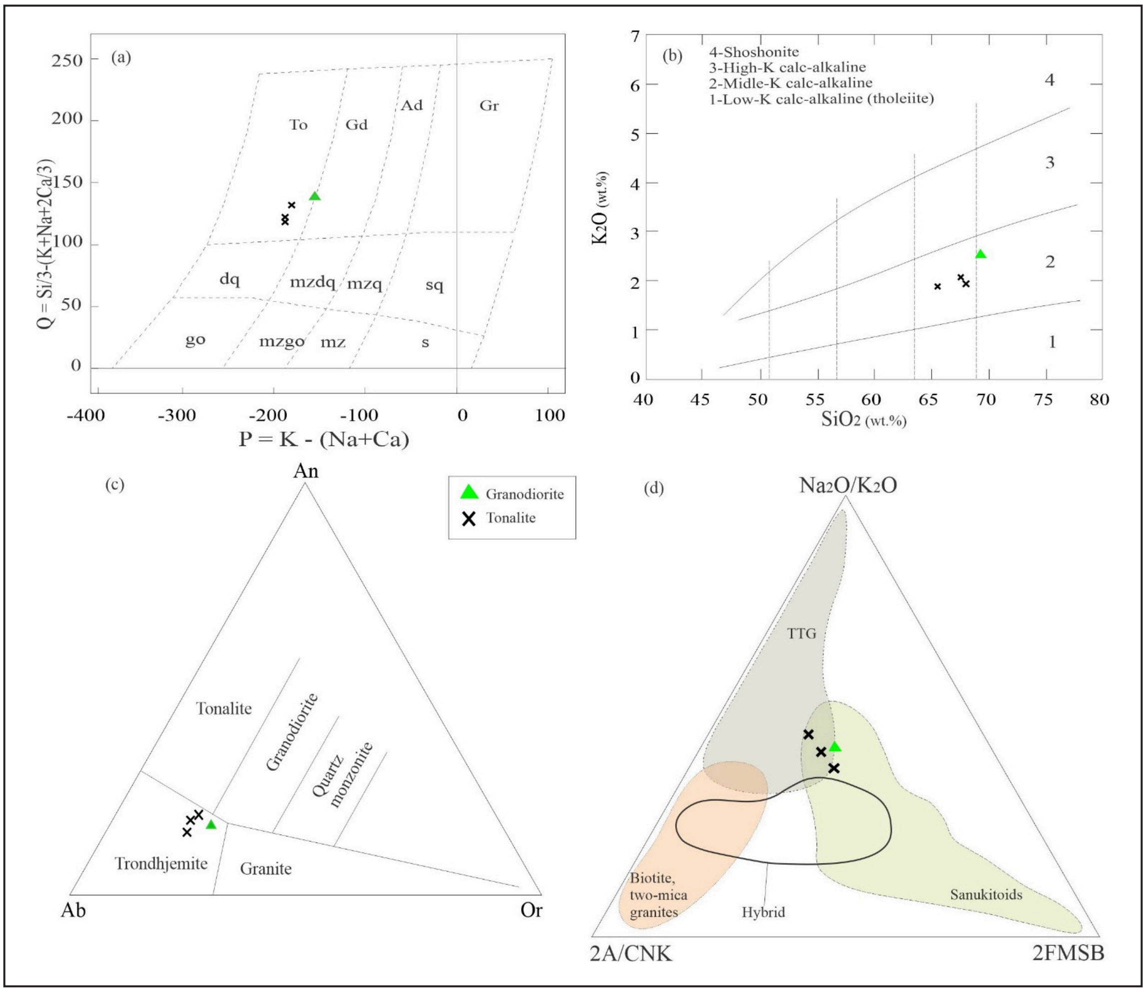

FIGURE 11. Geochemical plots showing the compositional characteristics of the tonalites in various discrimination diagrams. (a) P-Q diagram (Debon and Le Fort 1988); (b) SiO_2 vs. K_2O in the Peccerillo and Taylor (1976) diagram; (c) classification using normative Ab-An-Or (O'Connor 1965 with fields of Barker 1979); (d) ternary diagram from Laurent et al. (2014).

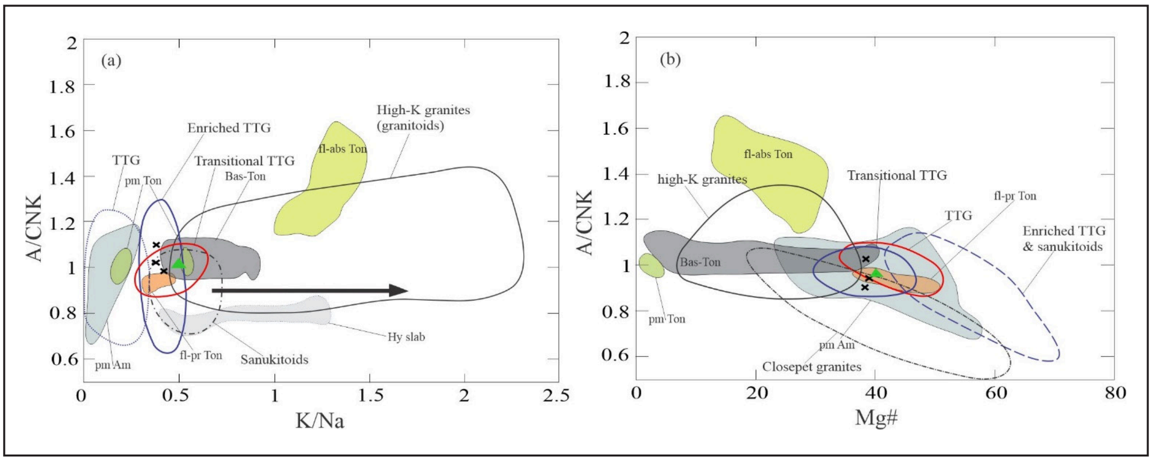

FIGURE 12. Bivariate plots of (a) K/Na vs. A/CNK and (b) A/CNK vs. Mg# for tonalites studied. Arrow marks the trend of increasing SiO_2. For comparison, the compositions of (enriched) tonalite-trondhjemite-granodiorite suites (TTG and enriched TTG), sanukitoids, Closepet-type granites, and K-granites from worldwide localities are marked (compiled by Moyen et al. 2003). The compositions of experimental melts were obtained by the partial melting of amphibolite/eclogite (pm Am) and tonalite (pm Ton) under water-present (fl-pr Ton) as well as water-absent conditions (fi-abs Ton) and by the interaction between basic magma, and tonalitic crust (Bas-Ton) are illustrated as grey shaded fields (data sources from Lopez et al. 2006, and reference therein). Symbols as Figure 11.

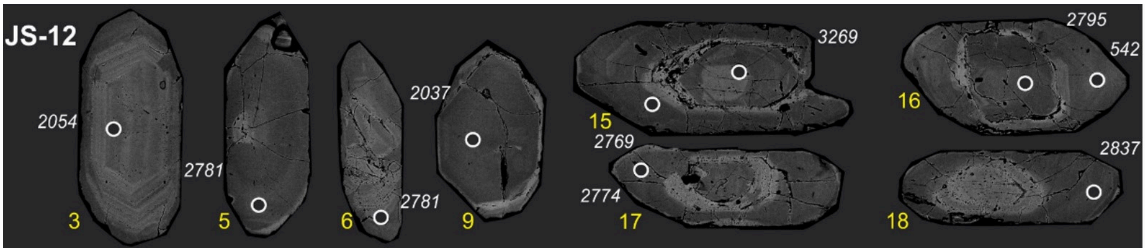

FIGURE 13. Backscattered electron images of zircon crystals from sample JS-12. The crystal numbers are identified in yellow. In italics, the ages obtained in the spots. For the Neoproterozoic data the $^{206}Pb/^{238}U$ apparent ages were used; for the older results of $^{207}Pb/^{206}Pb$ apparent ages are presented. All ages are in Ma. Figure 15 shows the localization of sample JS-12 (2.82 Ga), outside the domains known as Archean Goiás Massif.

8. Discussion

8.1. Limitations of the method

The gamma-ray spectrometric signature is not unique for any kind of rock. All geophysical methods have ambiguities, and they are minimized when using various methods and combined tools. Weathering fractionates the Uranium contents relatively to Thorium, which is a more resistant element to this process.

Some aspects, such as weathering, can modify the original proportion of radioactive elements. Leaching and variations in groundwater levels concentrate Thorium at the expense of Potassium and Uranium. For example, high-K granitoids and pegmatites or mafic rocks and water bodies may present the same signature. For instance, lateritic plateaus present a characteristic signature, especially when observed with a flat relief image, of high Thorium relative to Potassium and Uranium (cyan in the RGB image - K, eTh, eU). There are some Potassium-rich schists that show low Uranium and high Thorium and Potassium gamma-ray spectrometry signatures. It is important to observe that gamma-ray spectrometric signatures can represent ambiguity for certain rocks.

The gamma ray radiation is usually constrained from the upper 30 cm of the earth's surface, so that weathered materials are relevant for the resultant signal (Carrier et al. 2006; Wilford and Minty 2006). For instance, the loss of K in the soil can be used to estimate the degree of surface weathering and leaching, where the bedrock is composed of k-bearing minerals. On the other hand, Th and U are associated with more stable weathered materials in the soil profile. These elements are released during weathering and absorved onto clay minerals, oxides and organic matter. In addition, soil erosion can superimpose gamma-ray signature from *in situ* weathering (Reinhardt and Herrmann 2018). Finally, supergene processes produce U-enrichment and disturb the ratio of Th/U of the environments. Based on portable gamma-ray spectometry, Dessouky and Ali (2018) studied U-imigration over alkaline volcanic rocks in Egypt. The concentration of U is controled by i) geochemical conditions such as pH, temperature, syngenetic Uranium content, ii) a suitable carrier such as carbonates, iii) a convenient receptor or reductants such as Fe or oxy-hydroxide, and iv) litogeochemical traps. Therefore, a large-scale approach is required in order to evaluate these local effects due to variations in the terrain and tectonics.

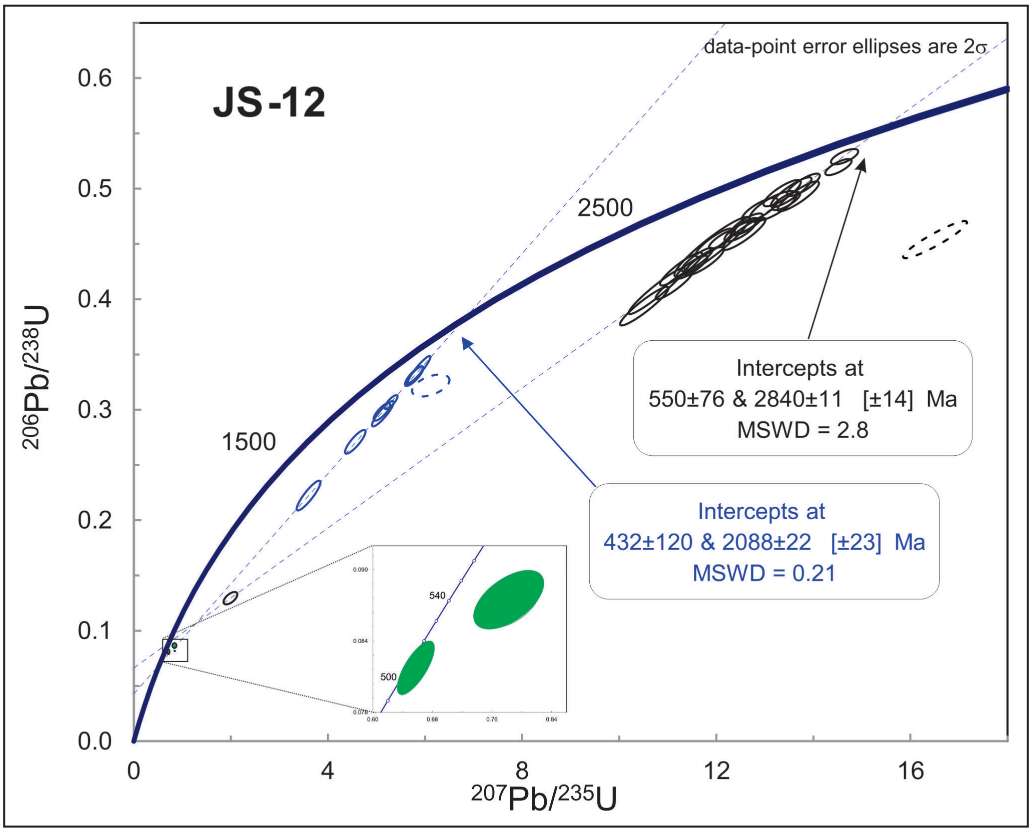

FIGURE 14. Concordia diagram for U-Pb results of sample JS-12. The dashed ellipses were used to represent data not used in the age calculation. The Archean, Paleoproterozoic and Neoproterozoic data are represented by black, blue and green ellipses, respectively.

In addition to the signature presenting very low Uranium in relation to Potassium and Thorium, the geometry of the gamma-ray spectrometry features combined with structural knowledge provide evidence of possible Archean terrains. The yellow signature (high K, medium-high eTh and low eU) in the ternary RGB image (K-eTh-eU) is not exclusive of TTG Archean terrains and, as all geophysical methods, can be ambiguous. However, considering several factors besides the geophysical signature, such as geometry, the nature of the structural emplacement and the proximity to terrains that have geology and geochronology already known and with similar radiometric characteristics, there is an indication that such characterization methodology is more robust, and the associated tools can suggest evidence for the Archean age in domains with this signature. There is a strong indication that such gamma-ray spectrometric domains are effectively associated with Archean TTG and that it is possible to characterize a potential signature with great discriminatory probability regarding the age of the rocks, although staying always aware of possible ambiguities.

8.2. Tectonic application

Two blocks known as Archean form an alignment in the direction of the Transbrasiliano Lineament (Pimentel et al. 2003). They are the Serra Azul Complex and the Archean block of Goiás. In this work we identified one more aligned fragment. This fact supports the hypothesis that the Transbrasiliano Lineament is the actor in the fragmentation of Archean blocks of common origin.

This type of signature was identified along the Moiporá-Novo Brasil transcurrent fault, considered as the boundary between the Archean Goiás massif and the Neoproterozoic arcs in addition to the discrimination of a fragmented lens following the N30ºE trend in the Transbrasiliano Lineament towards the TTG of the Goiás Serra Azul Complex. It can also elucidate a connection of these tectonically fragmented blocks along the Transbrasiliano and Moiporá-Novo Brasil lineaments, from Serra Azul Complex (to the north) to the edge of the Paraná Basin (to the south), allowing to suggest that the tectonic activity along the lineaments led to the transportation of the aligned terrain fragments, which originally could have been part of the of the presently covered Paranapanema block (Chiarini et al. 2013).

Archean-Paleoproterozoic terrains tectonically imbricated amid younger orogens are common during the crustal accretionary processes at some places in Brazil and worldwide (Brito Neves 2011; Condie 2013).

The identification of one more portion structurally aligned to the other, which is already known reinforces even more the hypothesis that these fragmented portions could be constituents of a common block.

8.2.1. Archean Goiás Massif

The Goiás Massif displays a series of magmatic pulses that evolved during the Archean, in which (i) the oldest complex (ca. 3.1–2.9 Ga tonalitic to granodioritic batholiths) are intruded by bodies of ca. 2.8 Ga tonalites, granodiorites, and monzogranites; (ii) the youngest complexes correspond to

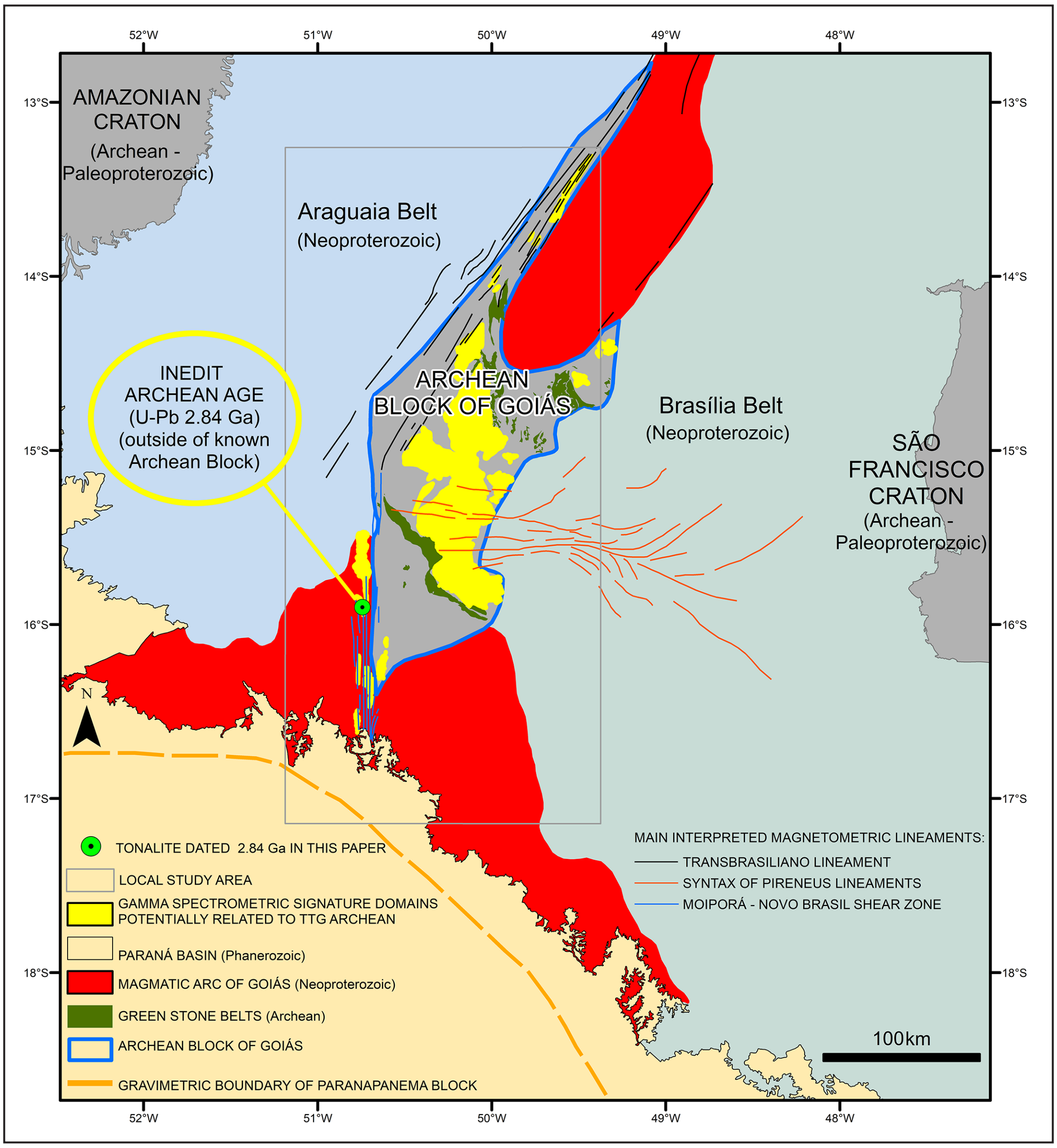

FIGURE 15. Archean rock (green dot) amid terrains mapped as Neoproterozoic. Based on Delgado et al. (2003).

an assembly of ca. 2.8 Ga tonalitic and granodioritic gneisses, considering that one of them is intruded by a younger magmatic rock consisting of granodiorites and granites of ca. 2.7 Ga. (Jost et al. 2013; Borges et al. 2021).

Granulitic metamorphism at 770-750 Ma is indicative of an early orogenic event of the Neoproterozoic, partially preserved in the Goiás Massif, but generally obliterated by the main metamorphic events that occurred between 650-600 Ma, related to collisional episodes that structured the entire Brasília Belt (Jost et al. 2013). Such events were responsible for the tectonic placement of the Goias Massif amid the Neoproterozoic magmatic arc terrains and possibly leaving Archean fragments in robust shear zones.

8.2.2. Serra Azul de Goiás Complex

This name was first given by Dantas et al. (2007) to characterize the occurrence of gneissic rocks in the homonymous ridge located in the central portion of study area. These rocks represent a set of banded biotite gneisses, with granitic to tonalitic composition, deformed and stretched, associated with migmatized zones bearing leucosome injections of syenogranite composition that indicate younger anactetic rocks. U-Pb zircon data of the Serra Azul gneisses define a crystallization age of around 2.9 Ga (Dantas et al. 2006; Fuck et al. 2006). The rocks of the Serra Azul de Goiás Complex are interpreted as an Archean lens tectonically imbricated in the rocks of the Neoproterozoic rocks, during the Ediacaran transcurrent and transpressional tectonic processes. Porangatu Complex methamorphic grade in granulite facies is aged between 570-580 Ma (Gorayeb et al. 2017).

The same gamma-ray spectrometric signature (high Potassium and Thorium; low Uranium contents) pattern is recorded in lenses further north, along the Transbrasiliano Lineament in the Tocantins Province, possibly forming a trail of mass movement of several fragments in the N30ºE direction. The contacts of these lenses, comprising mylonites, gneisses and granulites, are controlled by extensive transcurrent and transpressional shear zones that exhumed deep crust portions

(Figure 16). These Archean and Paleoproterozoic fragments removed from their blocks behave as exotic and allochthonous terrains in the subsequent orogenic cycles, especially during the Brasiliano Orogeny.

The Archean-Paleoproterozoic terrains of Crixás-Goiás are geographically closer to the basement of the Paraná Basin (about 50 km from gravimetric limit interpreted by the Paranapanema Craton, Figure 17) in relation to the distances to the São Francisco-Congo and Amazonian cratons. Additionally, the kinematic indicators suggest mass movement to NE (Transbrasiliano Lineament), compatible with the hypothesis that such terrains were possibly part of the Paranapanema Craton, transported and tectonically imbricated with the terrains of the Goiás Magmatic Arc at the end of the Neoproterozoic, with features directly associated with the movements of the Transbrasiliano Lineament.

The Transbrasiliano Lineament is a huge structure, more than 5000 km long, affecting several crustal blocks within the Tocantins Province. It stands out with strong gravimetric and magnetometric gradients, and has been seismically active with high frequency of instrumental seisms aligned in parts of its extent, displacing Phanerozoic units of the Paranaiba Basin with tailings of approximately 30 km (neotectonics). In addition, it controls the structuring (both shallow and deep) of the drainages in the Paraná Basin in the N30ºE direction. Within the Tocantins Province, it constitutes a 100 km wide, NE trending tectonic corridor, and should not be underestimated as to its potential for mass movement.

The possible interpretations and discussions are related to the possibilities of these fragments retaining common genesis and, in addition, being representatives of the closest and most structurally aligned Archean block, the Paranapanema Block.

9. Conclusions

Airborne gamma-ray spectrometry, applied with other geophysical and geological tools, can provide preliminary evidence for tracking Archean rocks (TTG). This increases the possibility of identifying Archean rocks due to their very low radiation emitted in the spectrum related to the Uranium decay series relatively to a medium to high Thorium and Potassium contents.

Based on the gamma-ray spectrometric signature, it was possible to identify a previously unknown Mesoarchean terrain (2.82 Ga) amid Neoproterozoic magmatic arc terrains.

Due to the metallogenetic importance associated with Archean terrains, the method developed in this study may assist mineral exploration. It is intended to apply the methodology developed in the southern region of the Tocantins Province, in order to identify possible new locations of Archean rocks, allowing to expand of the mineral prospecting potential of the region, in addition to the application of this method to the tectonic evolution of the Tocantins Province and of the Transbrasiliano Lineament.

We propose a new identification of Archean terrains amid rocks generated by Neoproterozoic magmatic arc processes, as well as its implication in the tectonic evolution of the Tocantins Province and in the understanding of the Transbrasiliano Lineament.

Archean fragments were identified tectonically embedded in the Transbrasiliano Lineament and outside the previously known limits of the Archean-Paleoproterozoic terrains of Crixás-Goiás. As the Transbrasiliano Lineament, in addition to the fragments identified in this work, also marks out the Archean Serra Azul de Goiás Complex and the Archean-

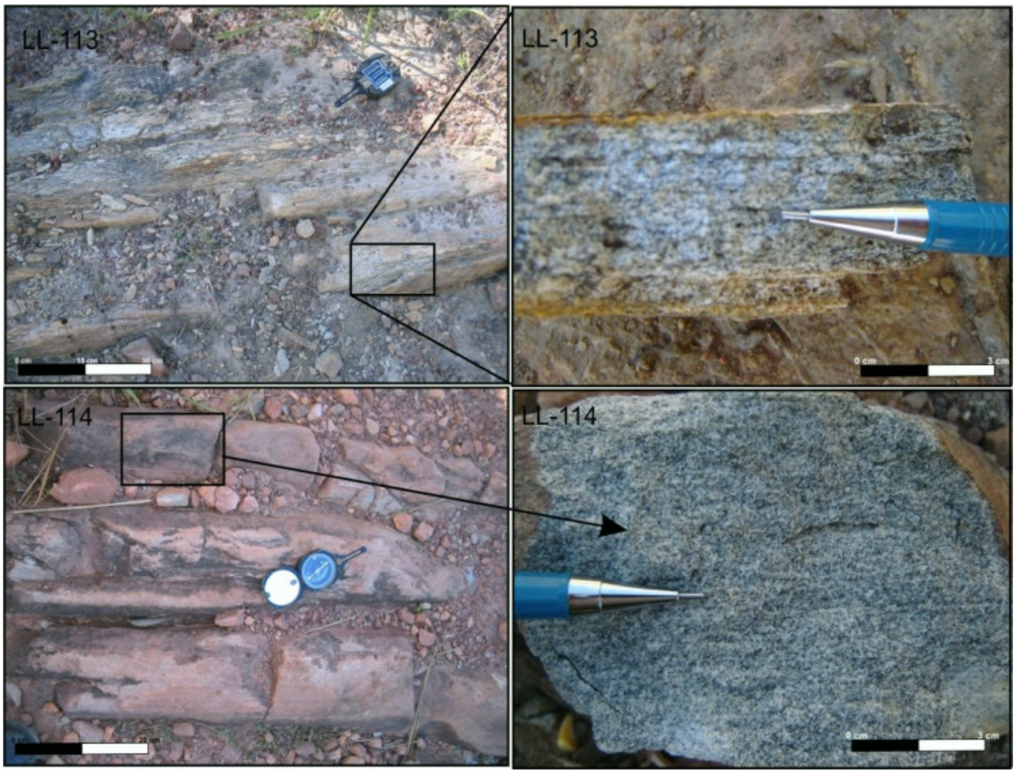

FIGURE 16. Mylonites and ultramylonites of granitic composition of the Serra Azul Complex (Archean), with high angle foliation located in the central portion of the Transbrasiliano Lineament. The rocks represent allochthonous terrains emplaced in high-grade metamorphic areas (Frasca and Ribeiro 2019).

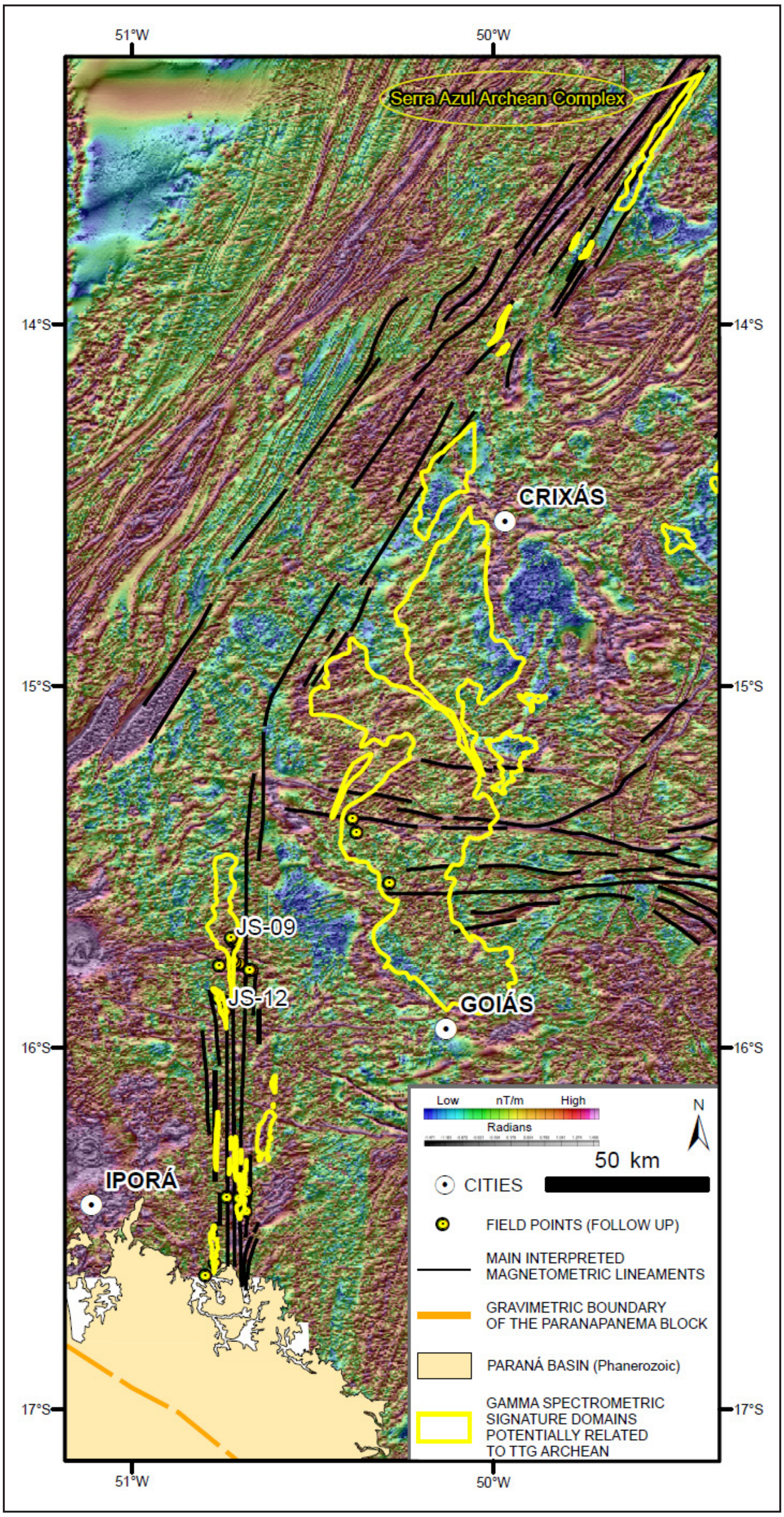

FIGURE 17. Total Gradient (colour) and Tilt derivative (gray) images composition (based on Correa et al. 2019) presenting E-W magnetic-structural framework corresponding to the domains of Archean Goiás Massif. Gamma-ray spectrometric signatures potentially related to Archean rocks are observed at the limit of the Paraná Basin imbricated in a N-S shear zone and approximately 30 km away from the gravimetric limit of the Paranapanema Archean Block. The Serra Azul Archean Block is also arranged in imbrication along the N31ºE shear zone (Transbrasiliano Lineament) strongly marked by high gradients and amplitudes in magnetometric images. This alignment of Archean fragments in continuous shear zones suggests a correlation of them.

Paleoproterozoic terrains of Crixás-Goiás, it is suggested that they belonged to the same block and that these terrains were segmented in Neoproterozoic. Due to the structural alignment and proximity of the gravimetric boundary of the Paranapanema Block, it is emphasized a possible genesis correlation between them. Such a hypothesis needs further studies.

9.1. Suggestions for future works

This work is intended to emphasize the potential of the gamma-ray spectrometric method and serve as an instigator for future studies.

We suggest mapping and isotope geology investigation to confirm the hypothesis presented in this study.

We recommend for future studies writing an algorithm using artificial intelligence, i.e. machine learning, for automatic search and statistical tests of accuracy with calculation of the percentage of success for the methodology.

We propose writing an algorithm to feed artificial intelligence in an attempt to automatically search for spectral signatures related to Archean rocks.

Also, we recommend for future studies a detailed mathematical analysis of the values contained in the trend corresponding to the Archean signatures, especially in the eU x eTh graph, as well as to determine which factor has correlation between the points of the other trends of linear trend graph eU x eTh.

We suggest isotopic and lithogeochemical drill holes analysis of the Paraná basin rocks to confront a possible association with Archean inliers along the Transbrasiliano Lineament in accordance with the tectonic evolution of this structure.

Perfoming geochronological Sm-Nd analysis is also recommended.

Acknowledgements

This paper and the research behind it would not have been possible without the support of CPRM (Companhia de Pesquisa de Recursos Minerais)/SGB (Serviço Geológico do Brasil). The authors would like to thank PhD Adino Américo Heimlich Almeida, member of Instituto de Engenharia Nuclear of CNEN (Comissão Nacional de Engenharia Nuclear), for the theoretical discussions. We would like to express our appreciation to PhD. Hardy Jost (in memorian), for the initial motivation and for the numerous geological contributions. We want to thank MSc. Tiago Bandeira Duarte for the micropetrographic analysis. We would like to express our gratitude to PhD. Lúcia Travassos da Rosa Costa, PhD. Marcelo Esteves Almeida, and PhD Luiz Gustavo Rodrigues Pinto for providing organizational and geoscientific support. We would also like to thank MSc. Iago Sousa Lima Costa and PhD. Roberto Gusmão de Oliveira for technical discussions. We would like to express our recognition and special thanks to the reviewers PhD. Lenka Baratoux and PhD. Denis Thiéblemont, and to associate editor of JGSB Martin Roddaz for previous contributions, that increased the quality of this work.

Appendices

Appendix 1. Analytical results of studied TTG.
Appendix 2. Table of U-Pb data from zircon of sample JS-12, obtained by LA-HR-ICPMS.

Authorship credits

Author	A	B	C	D	E	F
MFNC	■	■	■	■	■	■
LGM	■		■	■	■	■
ELD	■		■		■	
RAF	■		■		■	
EMGP	■	■	■			
RTC	■			■	■	
JES	■	■	■	■		
AASF				■		
JBR			■	■		
AMS				■	■	

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

References

Affonso G.M.P.C., Rocha M.P., Costa I.S.L., Assumpção M., Fuck R.A., Albuquerque D. F., Portner D.E., Rodríguez E.E., Beck S.L. 2021. Lithospheric Architecture of the Paranapanema Block and Adjacent Nuclei using Multiple-Frequency P-Wave Seismic Tomography. Journal of Geophysical Research: Solid Earth, 126(4), e2020JB021183. https://doi.org/10.1029/2020JB021183

Albarède F. 2009. Geochemistry: An Introduction. Cambridge, Cambridge University Press, 342 p. https://doi.org/10.1017/CBO9780511807435

Almeida J.A.C., Dall'Agnol R., Oliveira M.A., Macambira M.J.B., Pimentel M.M., Rämö O.T., Guimarães F.V., Leite A.A.S. 2011. Zircon geochronology, geochemistry and origin of the TTG suites of the Rio Maria granite-greenstone terrane: Implications for the growth of the Archean crust of the Carajás province, Brazil. Precambrian Research, 187(1-2), 201-221. https://doi.org/10.1016/j.precamres.2011.03.004

Barker F. 1979. Trondhjemites: Definition, environment and hypotheses of origin, In: Barker F. (ed.) Trondhjemites, Dacites and Related Rocks. Amsterdam, Elsevier. p. 1–12.

Benn K., Mareschal J.C., Condie K.C. 2006. Introduction: Archean geodynamics and environments. In: Benn K., Mareschal J.C., Condie K.C. (eds.) Archean geodynamics and environments. Washington, American Geophysical Union. p. 1-5.

Borges C.C., Toledo C.L., Silva A.M., Kirk J., Ruiz J., Chemale Jr. F., Sousa R.G., Santos B.A., Campos M.P., Campos L.M., Santos A.M. 2021. Archean to Paleoproterozoic evolution of the Crixás greenstone belt, Central Brazil: Insights from two contrasting assemblies of metaigneous rocks. Lithos, 404, 106493. https://doi.org/10.1016/j.lithos.2021.106493

Brito Neves B.B. 2011. The Paleoproterozoic in the South-American continent: Diversity in the geologic time. Journal of South American Earth Sciences, 32(4), 270-286. https://doi.org/10.1016/j.jsames.2011.02.004

Brito Neves B.B., Fuck R.A., Cruz Campanha G.A. 2021. Basement inliers of the Brasiliano structural provinces of South America. Journal of South American Earth Sciences, 110, 103392. https://doi.org/10.1016/j.jsames.2021.103392

Bühn B., Pimentel M.M., Matteini M., Dantas E.L. 2009. High spatial resolution analysis of Pb and U isotopes for geochronology by laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS). Anais da Academia Brasileira de Ciências, 81(1), 9–114. https://doi.org/10.1590/S0001-37652009000100011

Carrier F., Bourdon B., Pili É., Truffert C., Wyns R. 2006. Airborne gamma-ray spectrometry to quantify chemical erosion processes. Journal of Geochemical Exploration, 88(1-3), 266-270. https://doi.org/10.1016/j.gexplo.2005.08.053

Champion D.C., Sheraton J.W. 1997. Geochemistry and Nd isotope systematics of Archean granites of the Eastern Goldfields, Yilgarn Craton, Australia: implications for crustal growth processes. Precambrian Research, 83(1-3), 109–132. https://doi.org/10.1016/S0301-9268(97)00007-7

Chiarini M.F.N, Scandolara J.E., Saboia A.M. 2013 Projeto de interpretação e integração geofísica-geológica – Folha Araguapaz, Escala 1:100.000, CPRM.

Condie K.C. 2013. Preservation and Recycling of Crust during Accretionary and Collisional Phases of Proterozoic Orogens: A Bumpy Road from Nuna to Rodinia. Geosciences, 3(2), 240-261. https://doi.org/10.3390/geosciences3020240

Condie K.C. 2016. Earth as an Evolving Planetary System. Amsterdam, Elsevier, 418p. https://doi.org/10.1016/C2015-0-00179-4

Cordani U.G., Ramos V.A, Fraga L.M, Cegarra M., Delgado I., Souza K.G., Gomes F.E.M., Schobbenhaus C. 2016. Tectonic Map of South America, 2nd. ed., Escala 1:5.000.000. Paris, CGMW-CPRM-SEGEMAR. Available on line at: https://rigeo.sgb.gov.br/handle/doc/16750 / (accessed on 26 December 2023)

Correa R.T. 2019. Mapa radiométrico do Brasil, Escala 1:5.000.000. Brasília, CPRM. Available on line at: https://rigeo.sgb.gov.br/handle/doc/21296 / (accessed on 26 December 2023).

Correa R.T., Sordi D.A., Chiarini M.F.N. 2019. Mapa magnetométrico do Brasil, Escala 1:5.500.000. Brasília, CPRM. Available on line at: https://rigeo.sgb.gov.br/handle/doc/21299 / (accessed on 26 December 2023).

Dantas E.L., Araujo Filho J.O., Oliveira C.G., Fuck R.A., Pimentel M.M., Chiarini M.F.N. 2006. Isótopos de Nd na Determinação de Blocos Crustais na Região de Porangatu-GO. In: Congresso Brasileiro de Geologia, 43, 127. Available on line at: https://www.sbgeo.org.br/home/pages/44 / (accessed on 26 December 2023).

Dantas E.L., Araujo Filho J.O., Oliveira C.G., Chiarini M.F.N., Fuck R.A., Sordi D.A. 2007. Nota Explicativa da Folha Porangatu (SD.22-X-D-I). Escala 1:100.000. Brasília, UnB, CPRM, 59 p. Available on line at: https://rigeo.sgb.gov.br/handle/doc/10427 / (accessed on 26 December 2023).

Debon F., Le Fort P. 1988. A cationic classification of common plutonic rocks and their magmatic associations: principles, method, applications. Bulletin of Mineralogy, 111, 493-510.

Delgado I. M., Souza J. D., Silva L. C., Silveira Filho N. C., Santos R. A., Pedreira A. J., Guimarães J. T., Angelim L. A. A., Vasconcelos A. M., Gomes I. P., Lacerda Filho J. V., Valente C. R. Perrotta M. M., Heineck C.A. 2003. Geotectônica do Escudo Atlântico. In: Bizzi L. A., Schobbenhaus C., Vidotti R. M., Gonçalves J. H. (eds.) Geologia, tectônica e recursos minerais do Brasil: texto, mapas & SIG. Brasília, CPRM, 692 p. Available on line at: https://rigeo.sgb.gov.br/handle/doc/5006 / (accessed on 26 December 2023).

Dentith M, Mudge S.T. 2014. Geophysics for the Mineral Exploration Geoscientist. Cambridge, Cambridge University Press, 454 p. https://doi.org/10.1017/CBO9781139024358

Dessouky O. K., Ali H. H. 2018. Using Portable Gamma-Ray Spectrometry for Testing Uranium Migration: A Case Study from the Wadi El Kareim Alkaline Volcanics, Central Eastern Desert, Egypt. Acta Geolica Sinica, 92(6), 2214-2232.

Frasca A.A.S. 2015. Amálgamas do W-Gondwana na província Tocantins. PhD Thesis, Instituto de Geociências, Universidade de Brasília, Brasília, 172 p. Available on line at: https://rigeo.sgb.gov.br/handle/doc/15296 / (accessed on 26 December 2023).

Frasca A.A.S., Ribeiro P.S.E. 2019. Evolução crustal e metalogenia da porção centro norte da faixa Brasília: estados do Tocantins e Goiás. Goiânia, CPRM, 318 p. Available on line at: https://rigeo.sgb.gov.br/handle/doc/21486 / (accessed on 26 December 2023).

Fuck R.A., Dantas E.L., Pimentel M.M., Laux J.H., Junges S.L., Oliveira C.G., Sordi D.A., Chiarini M.F.N. 2006. The Santa Terezinha sequence, Goiás magmatic arc, central Brazil: constraints from U-Pb and Sm-Nd Data. In: South American Symposium on Isotope Geology, 5, 98-100. Available on line at: https://rigeo.sgb.gov.br/handle/doc/914 / (accessed on 26 December 2023).

Fuck R.A., Dantas E.L., Pimentel M.M., Botelho N.F., Armstrong R., Laux J.H., Junges S. L., Soares J.E., Praxedes I.F. 2014. Paleoproterozoic crust-formation and reworking vents in the Tocantins Province, central Brazil: a contribution for Atlantica supercontinent reconstruction. Precambrian Research, 244, 53–74. https://doi.org/10.1016/j.precamres.2013.12.003

Fuck R.A., Pimentel M.M., Alvarenga C.J., Dantas E.L. 2017. The northern Brasília belt. In: Heibron M., Cordani U.G., Alkmim F.F. (eds.) São Francisco Craton, Eastern Brazil.Berlin, Springer Cham. p. 205-220.

Hasui Y., Carneiro C.D.R., Almeida F.F.M., Bartorelli A. 2012. Geologia do Brasil. São Paulo, Editora Beca, 900 p.

Gorayeb P.S.S., Pimentel M.M., Armstrong R., Galarza M.A. 2017. Metamorfismo da fácies granulito em 570-580 Ma no Complexo Granulítico Porangatu, centro do Brasil: implicações para a evolução do Lineamento Transbrasiliano. Brazilian Journal of Geology, 47(2), 327-344. https://doi.org/10.1590/2317-4889201720160097

Jiang S., Wang R., Xu X., Zhao K. 2005. Mobility of high field strenght elements (HFSE) in magmatic-, metamorphic, and submarine-hydrothermal systems. Physics and Chemistry of the Earth, 30(17-18), 1020-1029. https://doi.org/10.1016/j.pce.2004.11.004

Jost H., Fuck R.A., Dantas E.L., Chiarini M.F.N., Mattos L., Oliveira R.C., Portela J. F., Rancan C.C., Rezende D.B., Santos E., Silva S.E.E. 2005. Geologia e geocronologia do Complexo Uvá, Bloco Arqueano de Goiás. Revista Brasileira de Geociências, 35(4), 563-576.

Jost H., Chemale Junior F., Dussin I.A., Tassinari C.C.G., Marti R. 2010. A U-Pb zircon Paleoproterozoic age for the metasedimentary host rocks and gold mineralization of the Crixás greenstone belt, Goiás, Central Brazil. Ore Geology Review, 37(2), 127-139. https://doi.org/10.1016/j.oregeorev.2010.01.003

Jost H., Chemale Jr. F., Fuck R.A., Dussin R.A. 2013. Uvá complex, the oldest orthogneisses of the Archean Paleoproterozoic terrane of central Brazil. Journal of South American Earth Sciences, 47, 201–212. https://doi.org/10.1016/j.jsames.2013.07.002

Laurent O., Martin H., Moyen J.F., Doucelance R. 2014. The diversity and evolution of late-Archean granitoids: Evidence for the onset of “modern-style” plate tectonics between 3.0 and 2.5 Ga. Lithos, 205, 208-235. https://doi.org/10.1016/j.lithos.2014.06.012

Lopez S., Fernandez C., Castro A. 2006. Evolution of the Archean continental crust: Insights from the experimental study of Archean granitoids. Current Science, 91(5), 607–621.

Ludwig K.R. 2012. User’s manual for Isoplot 3.75: a geochronological toolkit for Microsoft Excel. Berkeley Geochronology Center Special Publication, 5, Berkeley, 75 p.

Martin H. 1994. The Archean grey gneisses and the genesis of the continental crust. In: Condie K.C. (ed.) Proterozoic crustal evolution (Developments in Precambrian Geology). Amsterdam, Elsevier. p. 205-259.

McDonough W.F., Sun S.S. 1995. The composition of the Earth. Chemical Geology, 120(3-4), 223–253. https://doi.org/10.1016/0009-2541(94)00140-4

Moyen J.F., Martin H., Jayananda M., Auvray B. 2003. Late Archean granites: a typology based on the Dharwar craton (India). Precambrian Research, 127(1-3), 103–123. https://doi.org/10.1016/S0301-9268(03)00183-9

O’Connor J.T. 1965. A Classification for Quartz-Rich Igneous Rocks Based on Feldspar Ratios. US Geological Survey Profissional Papers, 525B, Reston, US Geological Survey. p. 79-84.

Oliveira F.V. 2015. Chronus: um novo susplemento para a redução de dados U-Pb obtidos por LA-MC-ICPMS. MSc Dissertation, Instituto de Geociências, Universidade de Brasília, Brasília, 91 p.

Peccerillo A., Taylor S.R. 1976. Geochemistry of eocene calc-alkaline volcanic rocks from the Kastamonu area, Northern Turkey. Contribution to Mineralogy and Petrology, 58, 63-81. https://doi.org/10.1007/BF00384745

Pimentel M.M., Jost H., Fuck R.A., Armstrong R.A., Dantas E.L., Potrel A. 2003. Neoproterozoic anatexis of 2.9 Ga old granitoids in the Goiás-Crixás Block, Central Brazil: evidence from new SHRIMP U-Pb data and Sm–Nd isotopes. Geologia USP, Série Científica, 3, 1-12. https://doi.org/10.5327/S1519-874X2003000100001

Pimentel M.M. 2016. The tectonic evolution of the Neoproterozoic Brasília Belt, central Brazil: a geochronological and isotopic approach. Brazilian Journal of Geology, 46, 67-82. https://doi.org/10.1590/2317-4889201620150004

Reinhardt N., Herrmann L. 2018. Gamma-ray spectrometry as versatile tool in soil science: A critical review. Journal of Plant Nutrition and Soil Science, 182(1), 9-27. https://doi.org/10.1002/jpln.201700447

Tapias J.G., Schobbenhaus C., Ramírez N.E.M. 2019. Geological map of South America, Escala 1:5.000.000. CGMW, Servicio Geológico Colombiano, CPRM. Available on line at: https://rigeo.sgb.gov.br/handle/doc/21606 / (accessed on 8 November 2022).

Turcotte D., Schubert G. 2014. Geodynamics. Cambrigde, Cambrigde University Press, 626 p.

Wilford J., Minty B. 2006. The Use of Airborne Gamma-ray Imagery for Mapping Soils and Understanding Landscape Processes. Developments in Soil Science, 31, 207-218, 609-610. https://doi.org/10.1016/S0166-2481(06)31016-1