

GAMMA SPECTROMETRY DATA SUGGEST OPPORTUNITIES FOR MINERAL RESEARCH IN ALAGOAS, BRAZIL

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ABSTRACT. This article presents the processing and quantitative interpretation outcomes of aero-gamma-spectrometric data within six regions renowned for copper and iron occurrences in Alagoas State, Brazil, situated within the geological framework of the Sergipian Orogen. The study primarily focuses on radioelement concentration data and its derived relationships, encompassing the creation of a ternary map and the utilization of targeting techniques to identify radiometric anomalies, such as potassium and anomalous uranium, along with the Factor F. These relationships enable the identification of behaviors associated with distinct geological models of mineralization, establishing connections between geophysical anomalies and well-known mineral occurrences. By integrating concentration information of radioelements K, Th, and U, in conjunction with geological data and existing mineralizations, the radiometric distributions of the region are thoroughly scrutinized. Radiometric ratios and ternary maps serve to facilitate the identification of enrichment centers for target minerals and the observation of desirable radiometric signatures. Hydrothermal enrichment enhancement techniques unveil a more pronounced correlation between copper targets and potassium (K) anomalies, whereas iron targets exhibit a relationship with uranium (U) enrichment. A ternary map, amalgamating anomalous potassium, K/Th ratio, and Factor F, aids in the identification of hydrothermal alterations. Magnetic maps emphasize anomalies near significant indications, accentuating structurally advantageous contours for hydrothermal enrichment and contacts with magnetic minerals associated with iron deposits. Future exploration endeavors should accord priority to these selected areas to unveil their mineral potential. Furthermore, the findings from this study offer valuable insights into the radiometric characteristics and their associations with ore deposits, thereby guiding investigations in other mineral-rich regions, always considering local geology as a vital initial datum.

Keywords: Gamma-ray Spectrometry Data; Mining Geophysics; Iron and Copper Ore Mineralization

INTRODUCTION

Copper and iron mining is an important activity in the mining industry. The concentration of radioelements is a subject that is also related to mining, as many minerals contain small amounts of radioactive elements, such

The current work was developed based on the processing and interpreting of aero-gamma-spectrometric data to characterize copper and iron occurrence zones and the correlation with new targets favorable for mineral exploration in state of Alagoas, northeastern Brazil. Inserted in the geotectonic context of the Borborema Province, this section is distinguished by shear features, which, according to [Mendes and Brito \(2017\)](#), represent passages between different geotectonic domains that comprise the studied region. This set includes the Pernambuco-Alagoas domain to the north, and the Canindé, Macururé, Marancó-Poço-Redondo, and Rio Coruripe domains, which compose the Sergipano Orogen to the south (Fig. 1). The region also features geological complexes with known iron formations, such as the Cabrobró Complex.

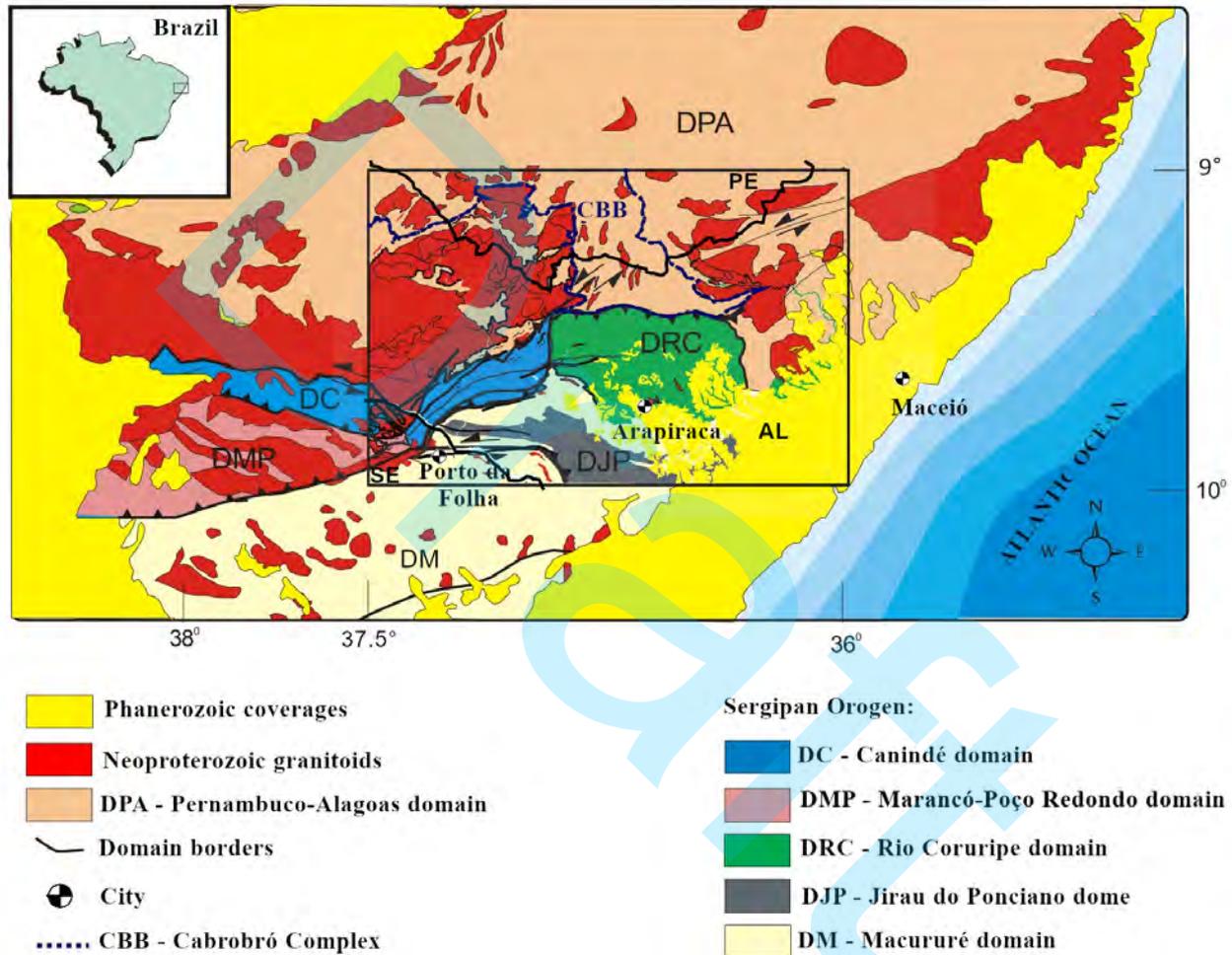


Figure 1: Geotectonic clipping of the Transition Zone between the Pernambuco-Alagoas (DPA) and the domains pertaining to the Sergipano Orogen

. Modified from [Mendes et al. \(2009\)](#) and [Santos et al. \(2021\)](#).

The gamma-spectrometric method refers to measurements of naturally occurring radioactive elements such as uranium, thorium, and potassium in rocks and soil. These elements emit radiation that specialized instruments can detect. Radiometric data is used to understand rocks' composition and identify areas of interest for mineral exploration. On the other hand, magnetic data is collected by measuring the magnetic field of the Earth's surface. This type of data can help identify the presence and distribution of magnetic minerals, such as magnetite, which can be used to infer geological structures and the history of tectonic activity.

As observed in work by [Sato et al. \(2013\)](#), an index (TC-ASA) based on total radio element count data and

analytical signal amplitude of magnetic data is developed, intending to reduce large areas with a probability of iron occurrence too small targets with higher favorability. The success of the methodology, applied to accurate data, occurs because of the geological characteristics of the analyzed iron formations. The increased presence of magnetite associated with metabasic rocks with a low concentration of radioactive elements allows the identification of environments with a higher potential for its occurrence.

It is worth highlighting here some studies that showed the feasibility of integrating gamma-spectrometric methods with other alternative methodologies in mineral exploration; one of these studies was developed in the mineral province of Carajás, developed by [Ferreira et al. \(2013\)](#), in which the efficiency of using unsupervised classification in radiometric data to differentiate ferritic formations from adjacent mafic rocks are noted. Still dealing with this same region, the paper published by [Hühn and Silva \(2018\)](#) uses gamma-spectrometry and its derived relationships as essential components for constructing the integrated mineral favorability map of the area.

The study carried out by [Ba et al. \(2020\)](#) promoted the integration of radiometric and magnetometric data in the mapping of dikes and structures favorable to the emergence of hydrothermal areas, thus verifying potentialities for the occurrence of minerals such as copper, with a greater focus on the identification of sulfide zones. Works like this, employing gamma-spectrometry in the identification of hydrothermal alterations, are common in the search for gold, as can be seen in the article published by [El-Sadek \(2022\)](#) in which the author applies methodologies such as the F-Factor and the anomalous K, also applied in the current work.

Given the variability of characteristics and results that can be extracted from aero-gamma-spectrometric data, this paper proposes to explore such versatility through quantitative and qualitative analyses that provide information associated with iron and copper occurrences in the northeastern part of Brazil, employing only gamma spectrometry as the primary method. The chosen study area has intense geological research and aero-geophysical data availability.

Thus, to characterize the areas of interest of the radiometric potential, analyses based on the statistical evaluation of the potassium, uranium, and thorium contents, ratios between these elements, and other methodologies associated with the identification of radiometric anomalies and their possible correlation with the mineral complex under study was used. According to the geophysical signatures to be determined, it becomes possible to prioritize mapping other areas inserted in this same geological context with a probability of presenting correlated mineralizations, stimulating new investigations and discoveries in the whole region. This work aimed to develop the geophysical characterization of the area using data from gamma-spectrometry, magnetometric campaigns, and auxiliary materials made available to accomplish this project.

DATA AND METHODS

The gamma-spectrometric data used in this research come from the Paulo Afonso-Teotônio Vilela aero-geophysics project (code 1104), carried out from September 16, 2010, to June 5, 2011, totaling 560 flight hours performed by *Microsurvey Aerogeophysics and Scientific Consulting Ltda*, in the service of Companhia de Recursos Minerais do Brasil. The survey covered an area of 40,819 Km^2 , encompassing sections of the states of Alagoas, Pernambuco, Bahia, and Sergipe ([CPRM, 2011](#)).

The main gamma-spectrometric information consists of the potassium, thorium and uranium concentrations

obtained in the referred survey (CPRM, 2011). Acquisition parameters employed for the project can be found in the table 1.

Table 1: Acquisition parameters extracted from CPRM (2011)

Acquisition Parameters	Specifications
Nominal height	100 m
Flight lines direction	N-S
Flight lines spacing	500 m
Flight lines amount	639
Control lines direction	E-W
Control lines spacing	10,000 m
Control lines amount	14
Gamma-spectrometer model	Pico Envirotec model GRS410/512-channel
Measurement interval	1 second
Airplane average speed	265 km/h

For this research, the information was grouped in a database and made available in corresponding formats, extracting the channels relative to the geographic positions and the contents of the radioelements K , eTh , and eU . The area defined for the research was reduced concerning the original acquisition coverage, aiming for more specific focuses by removing part of the Pernambuco-Alagoas domain.

Magnetic data directly relate to mineralizations and host rock's magnetic susceptibility variation. The interpretation of magnetic signatures helped characterize crustal structures and contact zones, evidencing possible exploratory targets.

Gamma-Ray spectrometry

The gamma-spectrometric method is based on the local count of the potassium, thorium, and uranium radioelements content from the energy measurement emitted due to their respective natural disintegrations (Minty, 1988). Despite its low depth range, it is the primary geophysical method used in geological mapping, providing lithological information as good as on-site surveys.

The total count is obtained by measuring gamma radiation within the energy window of 0.41-2.81 MeV. In this range, each radioelement is associated with a spectrometer channel with a peak energy signature of the isotope to be detected. In the case of uranium and thorium contents, these are, in practice, estimated from the radiation emitted by their daughter elements, bismuth (^{214}Bi) and titanium (^{208}Ti) respectively. Due to this measurement procedure, concentration values are given in thorium and uranium equivalents (Grasty, 1991).

The differentiated features among a K, Th, and U radioelements in rocks are attributed to their mineralogical composition, caused by internal factors, such as the geological evolution of the unit, or external ones, such as erosive processes that modify the recorded rates of each concentration. For example, the increased presence of silica in igneous rocks is usually related to elevations in U and Th contents. Thus, felsic rocks commonly

have higher concentrations of these radioelements if compared to mafic or ultrabasic igneous rocks (Dickson and Scott, 1997; Ribeiro et al., 2014).

In mining, applying radiometric methods extends beyond visualizing a lithological scheme. It allows interpreters to differentiate granitic bodies, secondary processes of surface coverage transformation, and possible mineralizations by hydrothermal fluids. These interpretations are facilitated by generating ratios and factors that evidence the anomalous values of these concentrations (Ribeiro et al., 2014).

Data Processing

The work was built following the flow presented in Figure 2, starting with processing the original gamma-spectrometric database. Then, the interpolation of the channels related to the potassium, uranium, and thorium contents was performed using the method of minimum curvature with a square and regular mesh with grid dimensions of 125 m x 125 m, equivalent to $\frac{1}{4}$ of the spacing between the flight lines.

Subsequently, the radiometric data were mean normalized to facilitate comparisons between sets of elements, eliminating the effects of influences and facilitating the visualization of anomalies. This way, ranges were established to classify the data into high, medium, and low concentration rates. For the range with high contents, the whole portion with contents higher than the average value of the set increased by one standard deviation is included. To be classified as an area with low concentration, the levels must be below the result of one standard deviation subtracted from the average value. The other regions that do not meet the above criteria were categorized as having medium concentrations.

The radiometric ratios K/eTh and eU/eTh were spatially constructed from the initial maps generated. These tools are usually employed to highlight differences in lithological compositions, especially in granitic (Ribeiro et al., 2014) bodies. Then, these products were also submitted to mean normalization procedures, aiming for more efficient visualization and behavioral mapping of these parameters in the study area.

The ternary map of the region was produced by applying histogram equalization using the RGB (Red, Green, and Blue) pattern. This composition associates red, green, and blue with the radiometric concentrations of potassium, thorium, and uranium. The interpretation of this map is widely used for geological mapping, highlighting contrasts between areas with different concentrations of the three elements. Furthermore, based on the concentration ranges of radioelements, a map of radiometric domains was made.

Additionally, the methodologies F-factor and anomalous potassium-uranium were applied. These are widely used in mineral research, especially in areas with hydrothermal fluid influence, a condition in some prominent regional mineral targets.

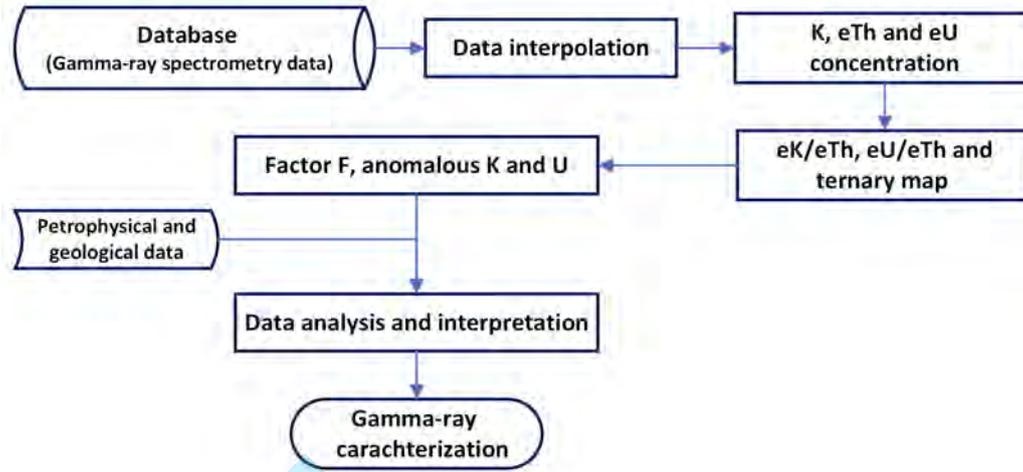


Figure 2: Flowchart applied to work.

To generate the **Factor F** (F) map, the equation 1 is employed. Originally proposed by Efimov (1978) where K represents the potassium concentration (%), eU , the equivalent uranium concentration (ppm) and, eTh , the equivalent thorium concentration (ppm). This factor was used to analyze the enrichment of potassium and uranium relative to thorium, another feature commonly observed in hydrothermal fluids due to the difference in mobility between (Ribeiro et al., 2014) radioelements.

$$F = K \times \frac{eU}{eTh}. \quad (1)$$

The second step applied, known as **Anomalous Potassium** (K_d), was initially used in Brazil by Pires (1995). The methodology is based on suppressing primary contributions of gamma radiation associated with factors such as lithology, soils, and environmental conditions. This effect is obtained through the equation 2, from which values of potassium (K_i) are generated as a function of Thorium (eTh) contents, the least mobile radioelement among the three, thus, hypothetically, preserving the primary contributions in the observed values of K .

$$K_i = \frac{K_{medio}}{eTh_{medio}} \times eTh, \quad (2)$$

The sought anomalous values (K_d), as shown in the equation 3, result from the difference between the predicted values of potassium (K_i) and the measured ones (K), whose anomalies represent the areas where secondary accumulations of this element can occur, a common factor in hydrothermally altered environments.

$$K_d = \frac{K - K_i}{K_i}. \quad (3)$$

Similar to the previously described methodology, the **Anomalous Uranium** (U_d) assumes the removal of primary gamma-spectrometric influences on the uranium concentration data. Thus, from obtaining the U_i (Eq. 4),

$$U_i = \frac{U_{medio}}{eTh_{medio}} \times eTh, \quad (4)$$

and deducing it from the observed values of eU , it is possible to obtain the anomalous contents (U_d), which theoretically represent uranium concentrations correlated to secondary enrichments (Eq. 5).

$$U_d = \frac{eU - U_i}{U_i}. \quad (5)$$

RESULTS AND DISCUSSION

The database used in this study played a pivotal role in providing essential statistical data for an assessment of the region under analysis, detailed in the table 2. In this article, a comprehensive analysis of these statistics was first carried out, shedding light on the key trends and patterns that emerged, providing valuable information on the dynamics and characteristics of the region.

Table 2: Statistical of gamma-ray measures database. Reference values extracted from [Ribeiro et al. \(2014\)](#) and [Sampaio and Silva \(2017\)](#)

Radioelement	Max	Min	Mean	Median	Std. Dev.	Reference value
K (%)	7.11	0.00	1.47	1.29	1.19	2.00 - 2.50
eTh (ppm)	50.34	0.00	14.98	12.79	8.26	5.80 - 12.00
eU (ppm)	14.32	0.00	1.67	1.50	1.10	1.30 - 3.00

The maximum values found in the gamma-spectrometric database presuppose the presence of positive anomalies in the region since they are above the reference ranges for such concentrations in the Earth's crust. However, a simple observation of the average and median values in the table shows that most of the area is below or within the base values for potassium and uranium contents, a trend not verified for thorium. This behavior of Th can be associated with the significant presence of gneissic and granitoid rocks in the geotectonic domains or with the relief characteristics, which strongly influence the concentrations of this radioelement.

Furthermore, concerning the values presented in the table 2, there is a proximity between the means and medians of the radioelements. This fact suggests that the gamma-spectrometric distributions are similar to normal histogram distributions. However, they have asymmetric silhouettes to the right since the median values are lower than the mean ones. Based on the standard deviations found, it can be stated that, except for thorium, there are no large dispersions of gamma-spectrometric contents in the area.

In a more accurate analysis, the geochemical database was divided into specific groups related to the main tectonic domains of interest and histograms were created to study the distribution of data among the main elements eU, eTh and K. Figure 3 presents the histograms of the databases of each of the radioelements of the main domains.

In Figure 3, for each geotectonic section, their own histograms related to thorium and uranium are visually similar, with the exception of the Macururé domain. Such a characteristic is not noticed with potassium. Furthermore, a higher density of both elements is noticed in DRC and DPA plots, mainly impacted by the large number of measurements in these areas.

Most of these histograms are asymmetric, with the mean outside the range's middle. When the skewness is towards the right, the median is smaller than the mean, while the asymmetry to the left means a median

more significant than the mean, as in the thorium histograms. Through the scatter plots, it is possible to see a predominantly linear trend relationship between the distribution of thorium and uranium. However, for the distributions of DPA and DRC, the largest geotectonic domains in extension, the aforementioned relationship is not well defined.

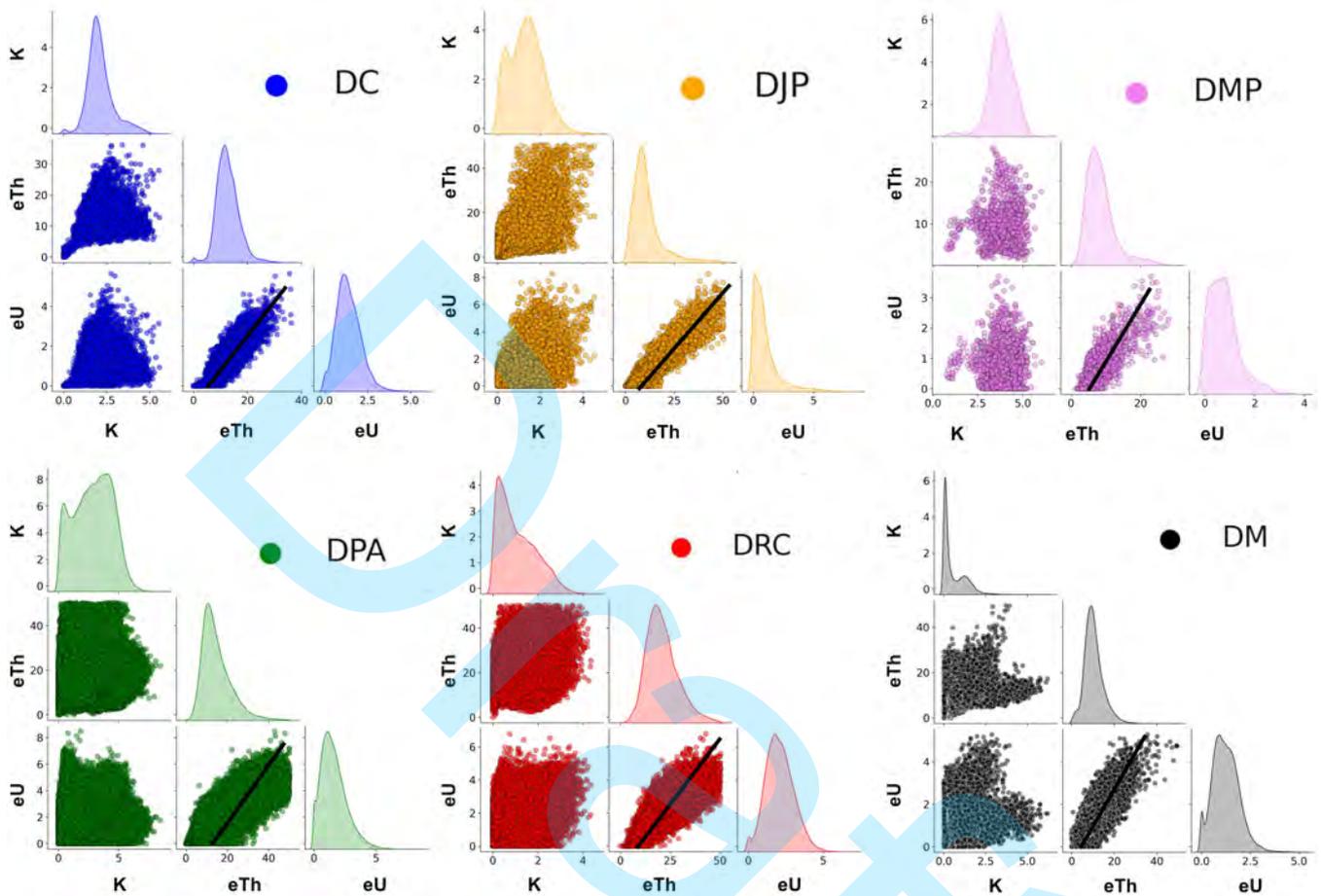


Figure 3: Histograms and scatter plots per geotectonic domain of the database. DC - Canindé Domain, DJP - Jirau do Ponciano Dome, DMP - Marancó Poço Redondo Domains, DPA - Pernambuco Alagoas Domin, DRC - Rio Coruripe Domain, DM - Macururé Domain.

Figure 4 shows a view of the potassium concentration map of the study area. In addition, Figure 5 shows the other two concentrations, related to the radio elements Th (A) and U (B), with the thorium map overlaid on the terrain relief to optimize interpretation. Examined by the Geological Service of Brazil (Mendes and Brito, 2017), the region reports approximately 160 mineral occurrences, 181 mineralization highlights, 133 geochemically anomalous stations, and evidence of hydrothermal alterations. From extensive on-site geologic mapping work, 11 mineral complexes have been restricted in the region, including six essential indications of a ferritic and/or cupriferous nature, explored throughout this paper. These selections, seen in Figure 4, fall within the Rio Coruripe (RC1, RC2, and RC3), Canindé (CN1), and Macururé (MC1) domains, and the dome structure of the Ponciano Jirau (JP1).

The mineral highlights in the center Figure 4 are associated with banded iron (RC1), copper, gold and massive iron (RC2), and massive magmatic iron (RC3) deposits of the Arapiraca Complex, in addition to iron concentrations in the Araticum Complex (CN1). In the lower section of the referred area, there are indications

of copper and fluorite mineralizations within quartz veins in the Macururé domain (MC1) and the presence of iron within the Nicolau-Campo Grande Complex (JP1) (Lima et al., 2017).

For the observation of radiometric concentration maps, the values exposed in the table 3 were used to establish the ranges of high, medium, and low classification values.

Table 3: Intensity of radiometric ranges used in the interpretation maps.

Radioelement	Low	Medium	High
K (%)	<0.28	0.28 - 2.66	>2.66
eTh (ppm)	<6.72	6.72 - 23.24	>23.24
eU (ppm)	<0.57	0.57 - 2.77	>2.77

Figure 4 shows the geographic distribution of potassium according to its concentration rates in the region, which ranges from 0 to 7.11 (%).

Observing the K map makes it possible to visualize the significant relationship between areas with recent sedimentary and hydrographic coverings with low potassium contents situated further to the southeast (A1). This behavior, present in areas with transported material, occurs due to the easy remobilization of this radioelement by erosive factors. Focusing on the portions with high K contents, the Marancó-Poço Redondo (DMP) and Pernambuco-Alagoas (DPA) domains stand out with alkaline intrusive suites, especially in the region of the Cabrobró complex (CBB) in the DPA. It is also the association between positive K anomalies and the mineral occurrence points classified by CPRM and represented on the map by blue circles for Cu occurrences and green circles for Fe occurrences, mainly located in the Rio Coruripe domain.

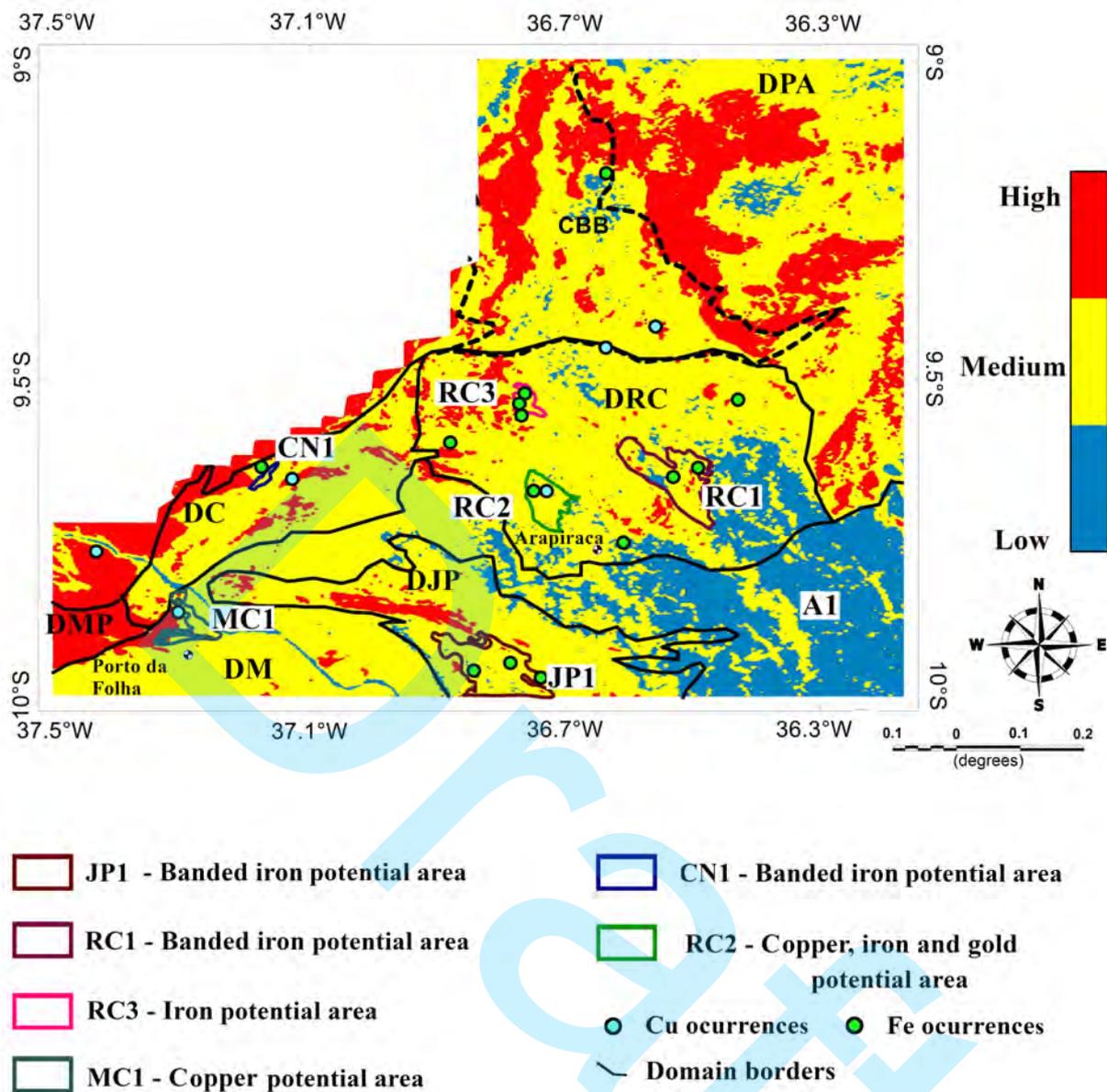


Figure 4: A) Potassium Concentration Map. Blue and green circles represent respectively indications of copper and iron occurrences extracted from Mendes and Brito (2017). DC - Canindé Domain, DJP - Jirau do Ponciano Dome, DMP - Marancó Poço Redondo Domains, DPA - Pernambuco Alagoas Domain, DRC - Rio Coruripe Domain, DM - Macururé Domain and CBB - Cabrobró complex.

The thorium spatial distribution map, shown in Figure 5 (A), displays high concentrations of this radioelement spread over the Rio Coruripe (DRC) and Pernambuco Alagoas (DPA) domains. The ppm content range is from 0.00 to 50.34 ppm. An essential feature of thorium is its lower ionic mobility among the three radioelements, tending its accumulations to regions with higher topographic elevations, noticed on the map in certain altitude points of the DRC and DPA (A2). Due to this more excellent resistance to weathering and erosion, areas with leaked material have lower thorium content than potassium and uranium. As a highlight on the map, we also notice a high concentration of eTh along an elongated band in the Ponciano dome (A3). Such a signature might be related to TTG-type granitic rocks, common in Archean/Paleoproterozoic rock complexes, previously noted by Rodrigues and Oliveira (2019).

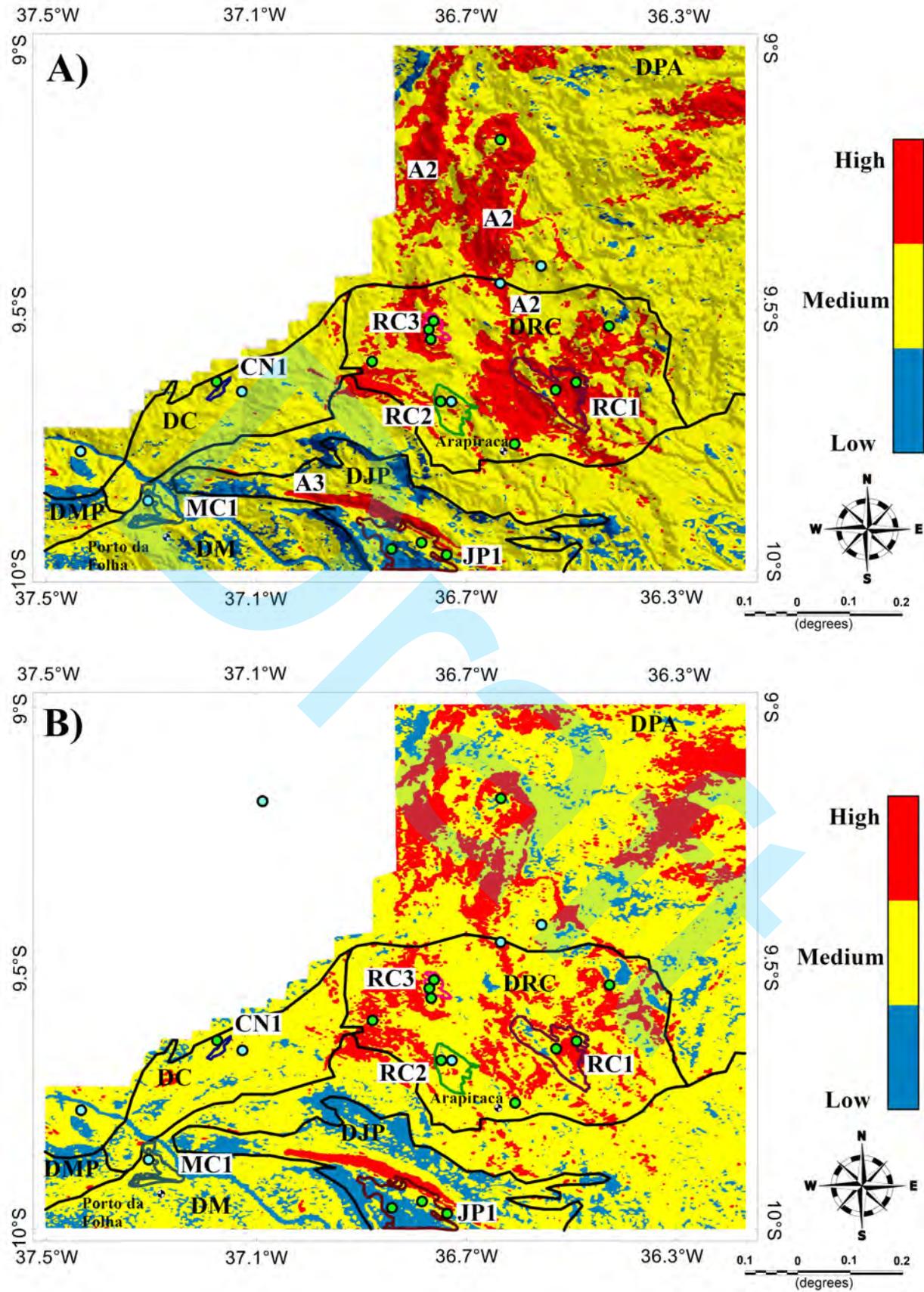


Figure 5: A) Thorium Concentration Map overlaid on the terrain relief. B) Uranium Concentration Map. Blue and green circles represent respectively indications of copper and iron occurrences extracted from [Mendes and Brito \(2017\)](#). DC - Canindé Domain, DJP - Jirau do Ponciano Dome, DMP - Maracó Poço Redondo Domains, DPA - Pernambuco Alagoas Domin, DRC - Rio Coruripe Domain, DM - Macururé Domain.

Despite its common correlation with thorium, uranium is a highly mobile element, forming soluble minerals and easily leached. This radioelement is usually related to pegmatites, syenites, carbonatites, granites, gneisses, and some shales but is seldom present in sandy sediments. The distribution of U in the map of Figure 5 (B) shows high concentrations in the Pernambuco-Alagoas DPA and Rio Coruripe DRC domains, as well as noted in the eTh map. Another expected movement can be visualized by looking at the more scattered patterns of high uranium concentrations similar to and associated with the hydrography of the region (Fig. 4 (A)). The ppm content range for Uranium is 0.00 to 14.32 ppm.

Ratios and Ternary Map

The variation in concentration among radioelements results from the local geology, especially the enrichment process (for example, by magmatic differentiation and/or hydrothermal action) and the degree of weathering suffered. Thus, images were generated representing the concentration of these elements and the ratios among them. Out of these, only a satisfactory view was obtained between the K/eTh and eU/eTh ratios, aiming at a better interpretation of the behavior of these elements in the study region.

The first mentioned ratio, shown in Figure 6 (A), stands out for its high values of this index allocated over the alkaline intrusive suites (A4) of the Pernambuco-Alagoas (DPA) and Marancó-Poço Redondo red(DMP) domains. Medium to high distribution patterns associated with hydrography is also seen since potassium enrichment in leaked areas is more common than thorium. In the Canindé domain (DC), high potassium values are observed beneath mineral indication points, forming linear bands oriented SW-NE. K enrichment in the MC1 deposit, associated with potassic hydrothermal alteration, and in JP1 in the Archean terrain of the Jirau do Ponciano dome (DJP), may also be pointed out.

The map of Figure 6 (B) is about a relationship between eU and eTh , radioelements with generally similar distributions but divergent mobility characteristics. Thus, this ratio's high values are expected in weathered areas, since uranium is more mobile than thorium. Another possibility associated with positive anomalies is the enrichment of uranium associated with potassium along the hydrothermal processes as opposed to thorium, a phenomenon between K and Th known as [Ostrovskiy \(1975\)](#) antagonism. From that principle, some points stood out on the map and were flagged (white boundaries). These points are geologically associated with a region characterized by undifferentiated granitoids resulting from late-stage plutonism (in the DPA domain) and a banded iron occurrence in the Arapiraca complex (DRC domain).

For the k/eTh ratio the range of values varies from -0.76 to 2.22, while for eU/eTh it ranges from -0.87 to 0.69.

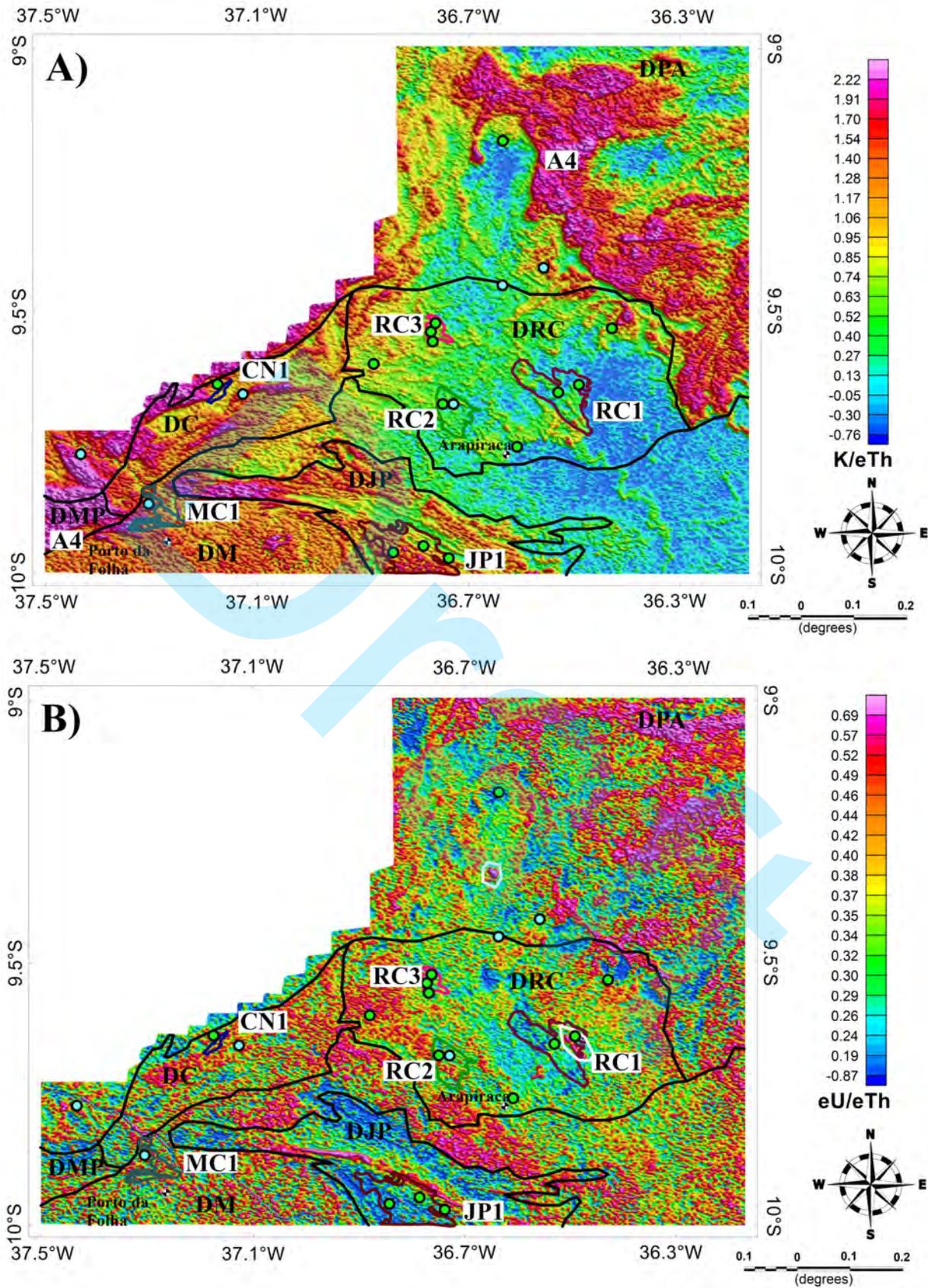


Figure 6: A) Potassium/Thorium Map. B) Uranium/Thorium Map. Blue and green circles represent respectively indications of copper and iron occurrences extracted from Mendes and Brito (2017). DC - Canindé Domain, DJP - Jirau do Ponciano Dome, DMP - Marancó Poço Redondo Domains, DPA - Pernambuco Alagoas Domain, DRC - Rio Coruripe Domain, DM - Macururé Domain.

In the ternary map (Figure 7 (A)), produced from the RGB color pattern, the colors representing the radiometric elements are associated with each of the vertices of an equilateral triangle. With varying gradations according to the three factor's content, white represents high counts of all elements. In contrast, the black color is associated with the low counts of the same ones (Ribeiro et al., 2014). In Figure 7 (A), a clear similarity (S1) is observed between the Rio Coruripe domain (DRC) and the central part of the Pernambuco-Alagoas domain (DPA), where the rocks of the Cabrobró Complex (CBB) are found. This terrain is more recent than the Arapiraca Complex, but both are known for hosting iron formations.

Still pointing out similarities, there is a high potassium concentration in the northeast region of the DPA in competition with the southwest of the map, in the Marancó Poço-Redondo (DMP), Canindé (DC), and Macururé (DM) domains, both regions with K-rich granites (S2). The southeast of the sheet is associated with surface coverings, sand, or leaching, with the bluish color showing uranium dominance. A quick observation can also bring us the perception of the prominence of the Jirau do Ponciano dome (DJP) in the area, with a brownish coloring in its edges, and enrichment of radioelements in its central region. The mineral occurrences of the paper, indicated by blue and green dots, are predominantly in light to bluish or reddish regions, strengthening the idea of metallic mineralization by secondary enrichments.

To enhance the analysis and better distinguish radiometric units with different compartments, a map of radiometric domains were made and arranged in Figure 7 (B). At first sight, practically homogeneous regions like the Canindé domain (DC), and more heterogeneous regions like the Coruripe River domain (DRC) are viewed. Most mineral occurrences are also associated with regions with colors representing the MHH, MMM and HMM categories. Based on this observation and recognizing that the same applies to the potential regions, the search for mineral targets should focus on areas with high/medium concentrations that exhibit similarities between thorium and uranium and high/medium concentrations of potassium.

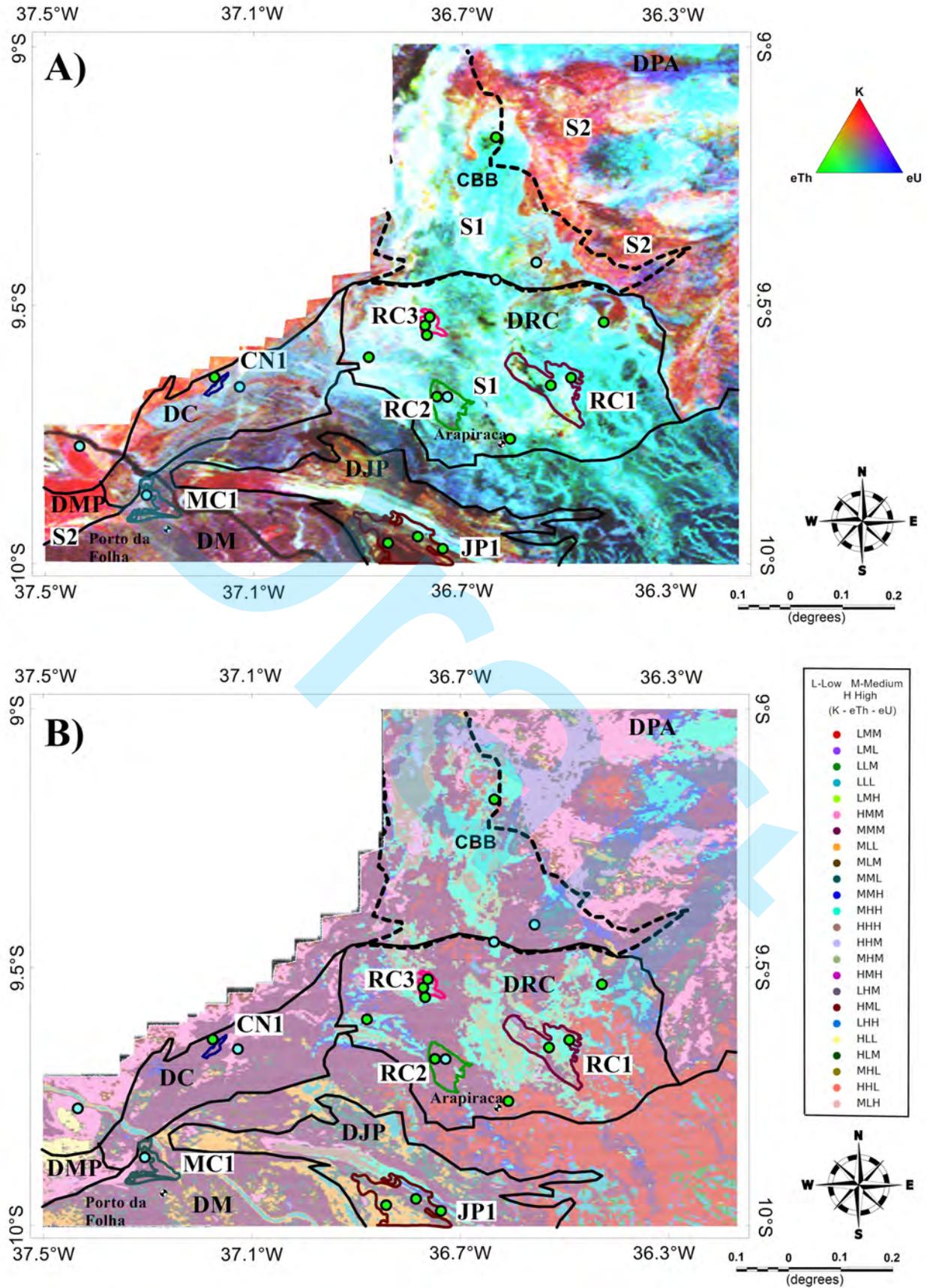


Figure 7: A) Ternary Map. B) Radiometric Domain Map. Blue and green circles represent respectively indications of copper and iron occurrences extracted from Mendes and Brito (2017). DC - Canindé Domain, DJP - Jirau do Ponciano Dome, DMP - Marancó Poço Redondo Domains, DPA - Pernambuco Alagoas Domin, DRC - Rio Coruripe Domain, DM - Macururé Domain and CBB - Cabrobró Complex.

F Factor, Anomalous K and U

In order to identify possible secondary hydrothermal enrichments, the maps shown in Figures 8 and 9 were elaborated.

The first map, named Factor F (Fig. 8 (A)), mainly highlights areas with increases in potassium associated with a decrease in thorium concentration. The values of this parameter range from -0.05 to 0.19, and this approach emphasizes the intrusive suites of the DPA and evenly the Canindé and Marancó-Poço Redondo domains. The area with the highest highlight is located near MC1, characterized by veins enriched with copper due to secondary factors. Furthermore, there is a significant correlation between mineral occurrence points with high values of this parameter. However, some exceptions near JP1 are associated with the Nicolau-Campo Grande banded iron complex's quartzitic, ultramafic, and metamafic rocks.

The second map (Fig. 8 (B)) results from the application of the anomalous K methodology. With values ranging from -4.92 to 4.47, the result shows again a high correlation between mineral occurrence points and peaks of this anomaly. It is important to note that JP1 was prominently featured in this analysis, suggesting that the correlation between potassium and thorium measurements may have influenced the results presented by Factor F. Once this influence is removed, it becomes clear that the presence of potassium enrichment in this potential area is a possibility.

The third applied methodology (Fig. 9 (A)) was based on the idea that potassium enrichment could be accompanied by secondary uranium enrichment due to its high mobility. However, although the mineral occurrences were positioned well under average to high values of Ud, the result was not satisfactorily correlated with the other two parameters, Factor F and Anomalous K. The values in this map range from -2.72 to 2.26.

Therefore, considering the two better results (Anomalous K and Factor F) taking into account the existing relationship between high K /eTh values and hydrothermally altered zones (MC1), a ternary RGB map was constructed, with the colors associated red, green, and blue, respectively, with Kd, Factor F, and K/eTh ratio. This map is presented in Figure 9 (B).

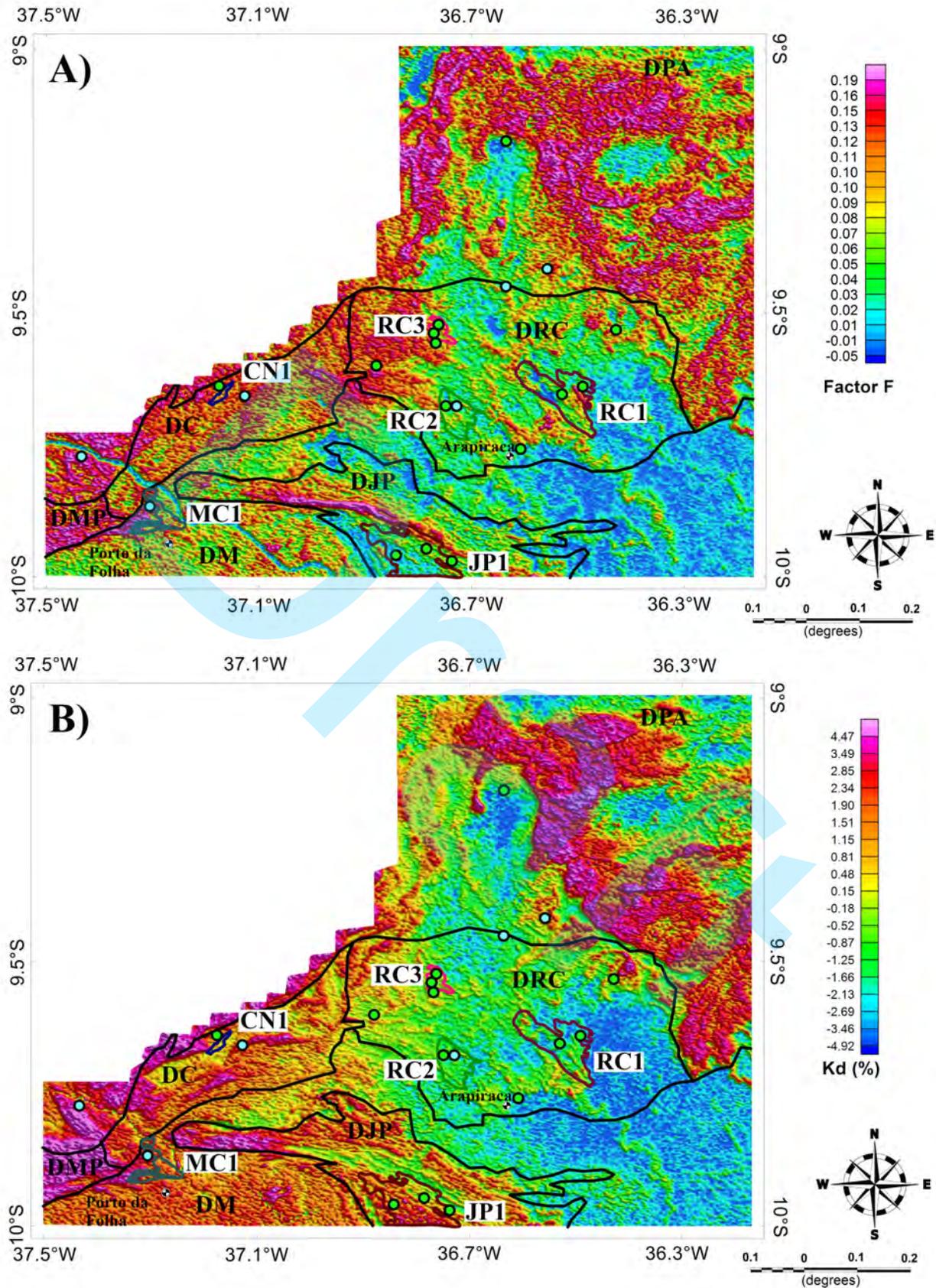


Figure 8: A) F Factor Map. B) Anomalous K Map. Blue and green circles represent respectively indications of copper and iron occurrences extracted from [Mendes and Brito \(2017\)](#). DC - Canindé Domain, DJP - Jirau do Ponciano Dome, DMP - Marancó Poço Redondo Domains, DPA - Pernambuco Alagoas Domin, DRC - Rio Coruripe Domain, DM - Macururé Domain.

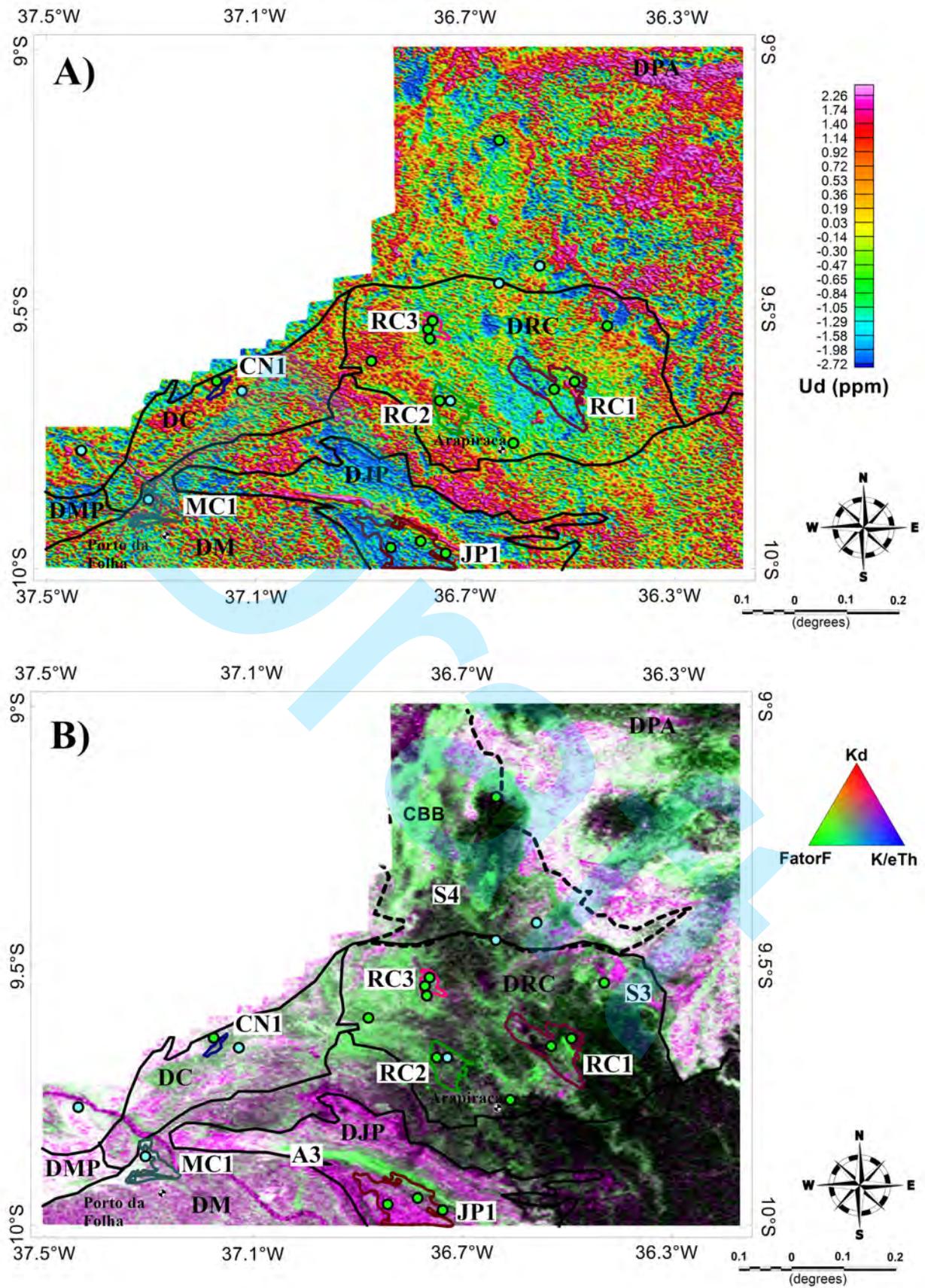


Figure 9: A) Anomalous U Map. B) Ternary Methodology. Blue and green circles represent respectively indications of copper and iron occurrences extracted from Mendes and Brito (2017). DC - Canindé Domain, DJP - Jirau do Ponciano Dome, DMP - Marancó Poço Redondo Domains, DPA - Pernambuco Alagoas Domin, DRC - Rio Coruripe Domain, DM - Macururé Domain and CBB - Cabrobró Complex.

When analyzing the new version of the ternary map (Fig. 9 (B)), it is observed that the majority of regions are filled with dark shades, indicating a lack of significant evidence for the components of the map. In addition to this pattern, three main trends can be identified in the study area: regions with high concentrations of the factor F (represented in shades of green), regions with high presence of Kd combined with the K/eTh ratio (shades of purple), and regions with a significant presence of all relationships (shades of white).

The Rio Coruripe domain (DRC) is notably associated with higher concentrations of the Factor F, as evidenced by the predominance of green shades in its area, encompassing the potential regions RC1, RC2, and RC3. However, there are exceptions with predominantly purple areas, especially in the region near the contact with Pernambuco-Alagoas at its northeastern border (S3). This trend in the transition zone between the domains extends throughout the rest of the terrain, up to the limits where the rocks of the Cabrobró Complex are found in the central portion of this area (S4). This visual correlation strengthens the hypotheses of common mineral associations between the regions, reinforcing the importance of these coincident signatures.

Along the regions near MC1, there is a strong relationship with white and purple shades, suggesting a high possibility of hydrothermal alteration. On the other hand, the Jirau do Ponciano dome exhibits distinct regions with the three main observed trends, highlighting the Nicolau Campo Grande complex in shades of purple and the anomalous region cutting across its structure, displaying shades of green (A3). Furthermore, the map delineates the boundaries of DJP, as this structure is an extrusive body in the region, distinct from the Macururé domain in which it is embedded. The contacts of this structure with other lithological units, outlined by strong shades of purple on the map, may provide spaces for the infiltration of hydrothermal fluids.

While primarily employed for detecting hydrothermal alterations, the association of copper with purple regions and iron with green regions can be established. As such, applying this correlation may offer a broader range of functionalities than initially anticipated.

Targets Selection

Upon completing and interpreting all previously generated maps, an exploration endeavor was initiated to uncover new prospects for iron and copper in light of the radiometric data. The methodological process entailed the extraction of values about the variables discussed throughout the article, including anomalous K (Kd) and K/eTh ratio, at locations corresponding to potential iron and copper mineral occurrences. Consequently, the data were segregated into two distinct databases, one dedicated to investigating iron-related patterns and the other to examining copper-related patterns.

An analysis of correlation coefficients and scatter plots among the investigated variables revealed that areas exhibiting copper mineralization display a significant spatial linear relationship among pairs of Factor F, anomalous potassium, and K/Th ratio data. Conversely, in the case of iron, this phenomenon was more pronounced between uranium concentration, anomalous uranium, and U/Th ratio. The specific values corresponding to these relationships for iron and copper can be observed in Figures 10 (A) and 10 (B), respectively.

Among the selected correlations for iron, the most notable is the association between U/Th ratio and Ud (0.84). Conversely, in the copper mapping, the focal point lies on Kd and K/Th ratio (0.99). These findings indicate that uranium enrichment plays a significant role in regions with iron occurrences, while in copper-rich regions, potassium assumes greater importance.

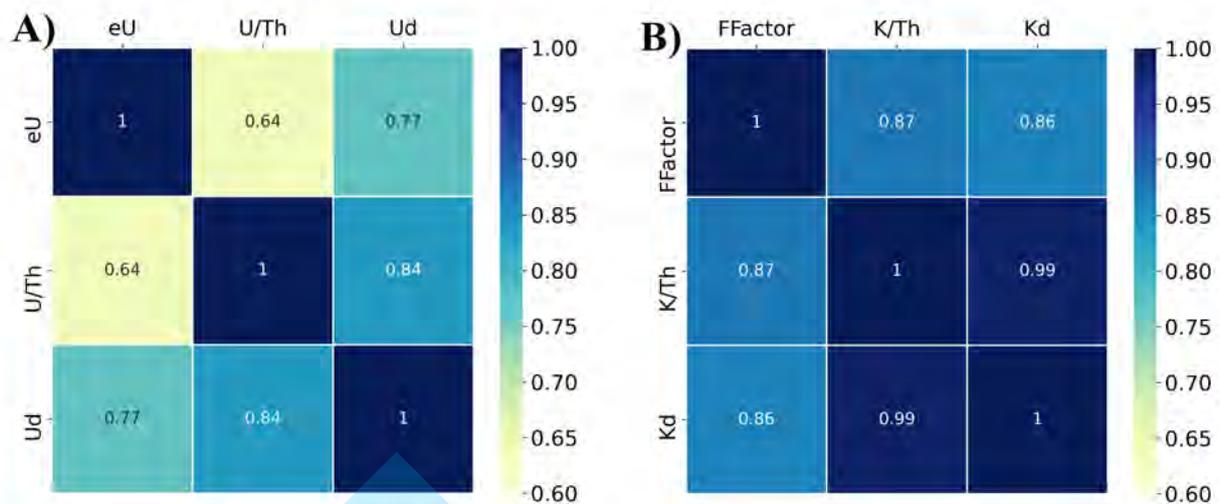


Figure 10: A) Prominent correlation indices were observed among the areas with iron occurrences. B) Prominent correlation indices observed among the areas with copper occurrences

The selection of areas was conducted through statistical means, utilizing specific relationship values for each type of ore, as depicted in Figure 10. Employing a filtering criterion, areas were chosen when their concentrations surpassed the threshold defined by the mean values of regions with copper and iron mineral occurrences, augmented by 2 standard deviations. This meticulous approach ensured a more precise identification of areas of interest.

Magnetic Results and Potential Area Evaluation

Combining the results of magnetic surveys can create detailed maps of the subsurface geology, which can help identify areas where mineral deposits may be present. These techniques were instrumental in mineral exploration because they can detect mineral deposits that may be hidden beneath layers of sediment or other types of rock.

However, it's important to note that magnetic surveys alone cannot determine mineral deposits' exact location or quality. They are typically used with gamma-spectrometry and geological sampling to provide a more comprehensive picture of the subsurface geology and the potential for mineral resources.

Integrating these techniques also helps to reduce exploration risks and costs by enabling more focused exploration efforts. For instance, if a magnetic anomaly is detected in an area of high gamma radiation, and geological sampling indicates the presence of mineralization, further exploration efforts can be targeted to determine the size, quality, and potential economic viability of the deposit.

In short, combining the results of magnetic surveys with gamma-spectrometry and geological sampling can provide a more comprehensive and accurate understanding of the subsurface geology and potential mineral resources and help focus exploration efforts on areas with the highest potential for success.

Since magnetic data provides results of bipolarized anomalies, one of the best ways to define and map relevant magnetic contours, contacts, and bodies is through the Amplitude of Analytic Signal (ASA) linear transformation applied to the original data. Such derivation can be observed in the map depicted in Figure 11, ranging from 0.011 to 0.629 nT/m. High amplitude sections are highlighted in pink, while low magnetic values are represented in green to enhance visualization contrast.

Upon observing the studied region, we note a highly rugged magnetic relief, particularly in the Pernambuco-Alagoas domains (DPA), characterized by various SW-NE magnetic lineaments in the outer portions of the Cabrobró Complex (CBB), and in the Rio Coruripe Domain (DRC) with NW-SE oriented structures. Another noteworthy point is that, in addition to similar radiometric signatures, the CBB and DRC exhibit comparable magnetic anomaly distributions. Moving on to the potential areas, we observe high ASA values outlining RC1, RC2, RC3, and MC1, suggesting the delineation of ore body contacts. As for CN1, this section is intersected perpendicularly by a magnetic structure, and MC1 does not display significant magnetic prominence, except for the elongated structure to the southeast (A5), as an extension of the body further southwest at the boundary between DM and DMP.

Overlaying the target indications from the aero-gamma-spectrometric data survey onto the Amplitude of Analytical Signal (ASA) map (Fig. 11), we notice the coincidence between high magnetic anomalies and indications primarily related to Iron (green circles).

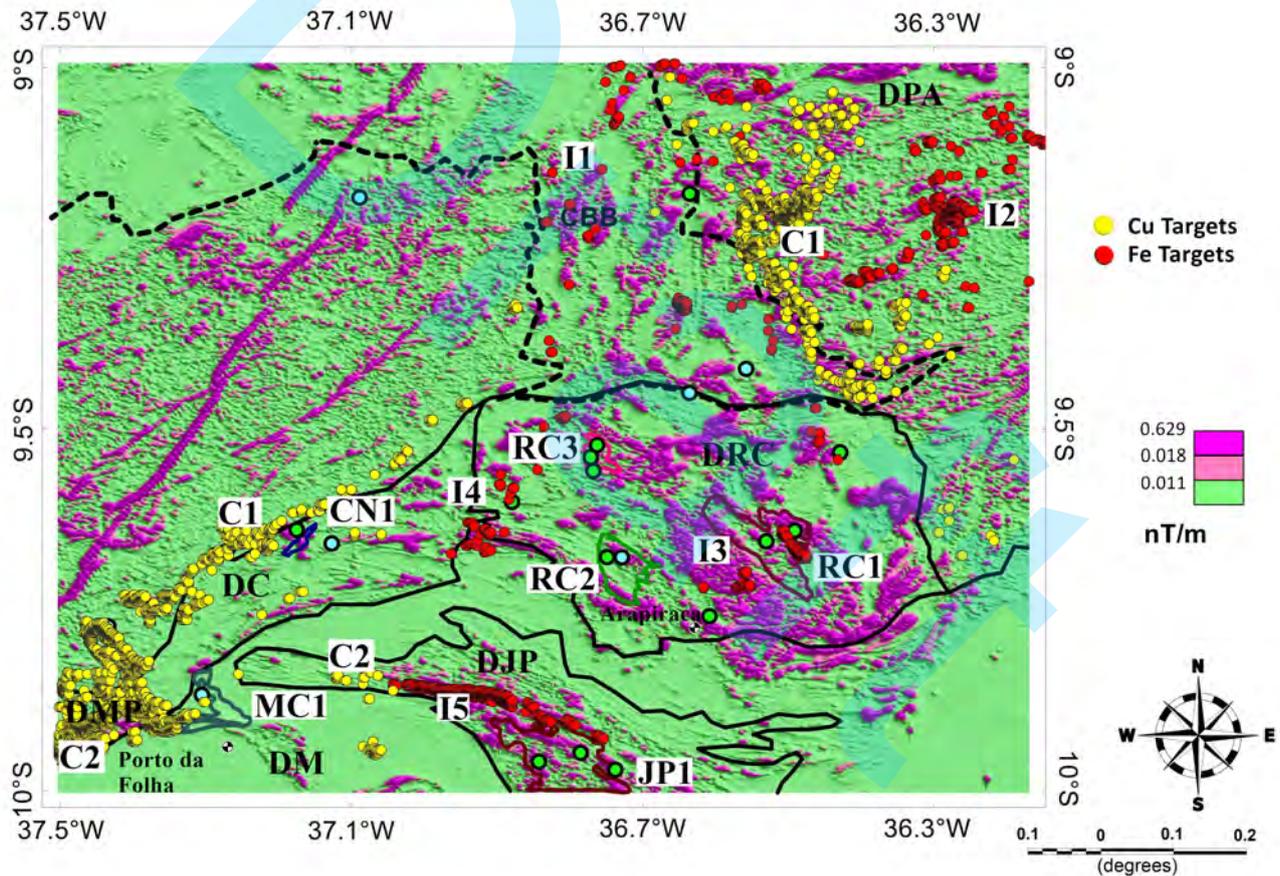


Figure 11: Map of the analytical signal amplitude of the magnetic datum with overlays of the iron targets, in red, and copper, in yellow. Blue and green circles represent respectively indications of copper and iron occurrences extracted from [Mendes and Brito \(2017\)](#). DC - Canindé Domain, DJP - Jirau do Ponciano Dome, DMP - Marancó Poço Redondo Domains, DPA - Pernambuco Alagoas Domain, DRC - Rio Coruripe Domain, DM - Macururé Domain and CBB - Cabrobró Complex.

Regarding the iron targets, they were prominently identified along the lithological units of the Cabrobró Complex (I1), indiscriminate granitoids (I2) in the Pernambuco-Alagoas domain, and the RC1 regions (I3) in the Rio Coruripe domain, as well as their boundaries with the Canindé Domain (I4). Additionally, notable

indications were also observed near the Nicolau-Campo Grande Complex (I5), close to JP1.

Concerning copper targets, the emphasis is mainly on the regions with higher potassium concentration, such as the Pernambuco-Alagoas domain, with potassium-rich granitic intrusions (C1), and the southwestern boundary (C1) between the Canindé domain and the Pernambuco-Alagoas domain. Despite the wide distribution of potential copper indications masked by lithologies with high potassium concentrations, the targets distributed along the Jirau do Ponciano dome's western tip (C2) and the numerous spots (C2) in the Marancó-Poço Redondo domain stand out. In addition to all the targets near MC1 in the Porto da Folha region, official observations of potassium alteration and copper mineralization in veins were made.

In order to filter the targets obtained in this study and better delineate the new areas with iron and copper mineral potential, the map shown in Figure 12 was generated. The criteria used favored regions with rugged magnetic relief, proximity to peaks of the analytic signal amplitude, and faults or shear zones. Regions with verified mineral occurrences (represented by white circles) and the zones of original potential areas were also highlighted. Furthermore, regions with a significant lithological influence from the granitic intrusions in the region were not entirely considered.

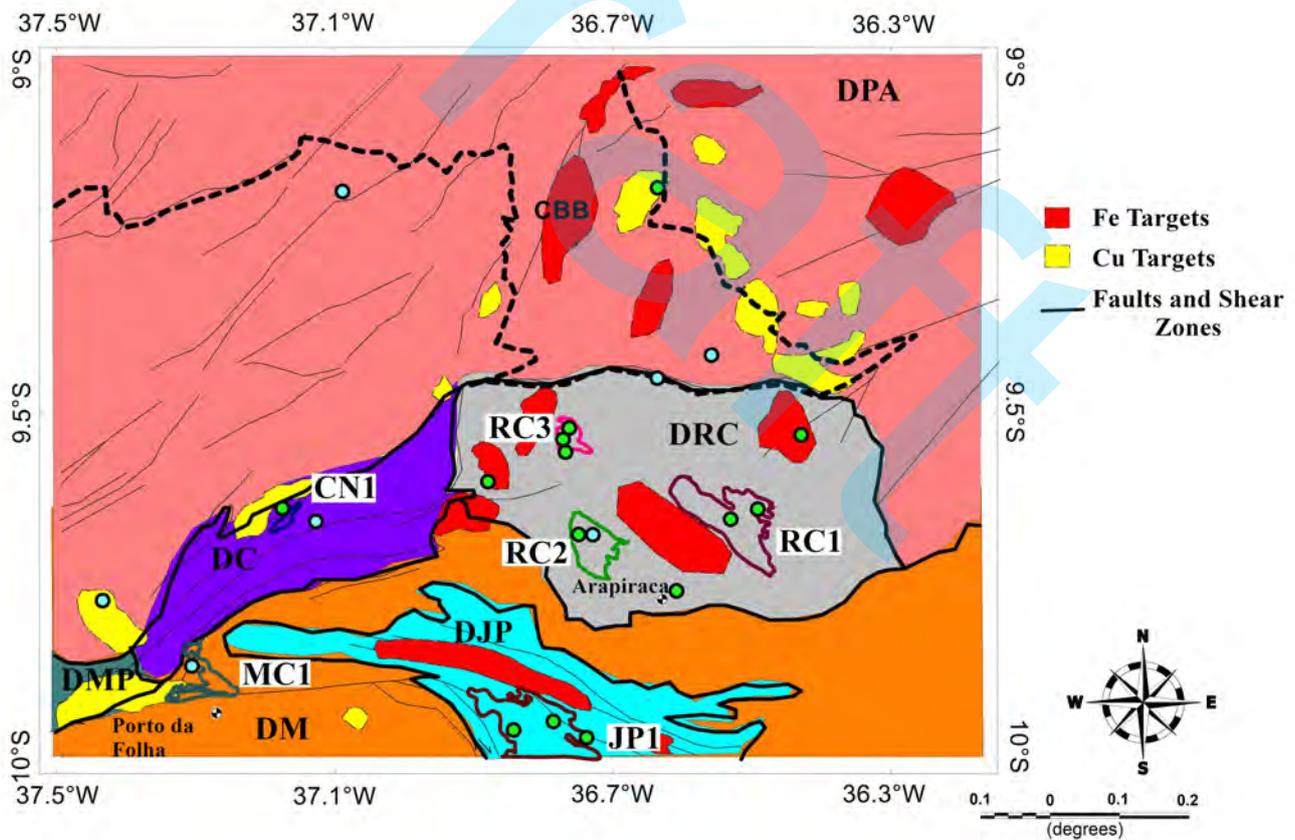


Figure 12: Illustrative map of the investigated region with indications of potential areas for the occurrence of Iron, in red, and Copper, in yellow. Blue and green circles represent respectively indications of copper and iron occurrences extracted from Mendes and Brito (2017). DC - Canindé Domain, DJP - Jirau do Ponciano Dome, DMP - Marancó Poço Redondo Domains, DPA - Pernambuco Alagoas Domin, DRC - Rio Coruripe Domain, DM - Macururé Domain and CBB - Cabrobró Complex.

CONCLUSION

In conclusion, mineral exploration is important for economic development and sustainable growth. Identifying and developing mineral deposits is crucial to meet the rising global demand for natural resources. This study used geophysical techniques to investigate new possible mineralization targets for iron and copper, two essential products in modern industries. It is important to point out that geophysical research has contributed with insights and information that are highly useful in the search for minerals. However, consolidations of occurrences must be made by field geological surveys.

By utilizing concentration information of the radioelements K, Th, and U, we were able to gain insights related to the radiometric distributions of the region, along with geological information and pre-existing mineralizations in the area. The use of radiometric ratios and ternary maps aided in identifying desired radiometric signatures, possibly associated with the target minerals.

As a complementary methodology, hydrothermal enrichment enhancement procedures were crucial, showing that copper targets had a stronger correlation with potassium (K) anomalies, while iron targets were directed towards regions with uranium (U) enrichment. Among these, the ternary map composed of anomalous potassium, K/Th ratio, and F factor was highlighted for hydrothermal alteration identification. This relationship was important in indicating the occurrence patterns of areas with iron and copper indications, as the present radiometric associations were displayed in shades of green for Fe and purple for Cu.

The association with the magnetic map highlighted the presence of anomalies near important indications, emphasizing structurally favorable contours for hydrothermal enrichment and contacts between bodies that may contain magnetic minerals, geologically associated with iron deposits.

As a suggestion for future work, it would be interesting to integrate a broader and more detailed range of data, especially petrophysical data located in the target areas selected for final investigation. Furthermore, considering the significant lithological potential of the region and its spatial extent, it is recommended to explore artificial intelligence methods to enhance research. Utilizing or testing such methods could provide more efficient and accurate results in the search for relevant information.

Additionally, it would be important to refine the criteria for target indication, considering not only geological and geophysical factors but also social and environmental information that can contribute to minimizing potential impacts in implementing a mineral project.

Overall, it can be said that integrating radiometric geophysical techniques into the mineral exploration workflow offers significant efficiency, cost-effectiveness, and environmental management benefits. These methods play a key role in optimizing exploration efforts, improving the accuracy of resource assessment, and promoting sustainable practices in the mining industry. As such, they should be considered essential tools in the toolbox of modern mineral exploration strategies.

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AUTHOR CONTRIBUTIONS

Sampaio, M.R.C.: Conceived and designed the study, collected and analyzed the data, interpreted the results, and wrote the initial manuscript draft. Actively participated in the discussion of results, provided critical feedback, and approved the final version of the manuscript. **Dutra, A. C.:** Contributed to the study design, conducted experiments, performed data analysis and interpretation, and drafted manuscript sections. Actively participated in the discussion of results, critically reviewed and revised the manuscript, and Approved the final version. **Flores, O. H. D. J.:** Provided substantial intellectual input during the study design, data analysis, and interpretation of the results. Drafted sections of the manuscript, actively participated in the discussion of results, critically reviewed the manuscript, and approved the final version.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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