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Radiometric Characteristics of the Lagoa Real Uraniferous Province, Brazil

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ABSTRACT

The present work proposes the evaluation of radiometric data of Uranium, Thorium, and Potassium concentrations in the Lagoa Real Uraniferous Province, Brazil. The data obtained from the São Timóteo project allowed to construct Uranium, Thorium, Potassium, and Total Count distribution maps. The results were compared with the geological and topographic maps. It allowed us to identify the main geological bodies of the region and to evaluate the natural radioactivity in the albitite formations which are rich of uranium ore in the Lagoa Real Intrusive Suite. Therefore, the research presents the characterization of the subsurface geological structures associated with uranium mineralization zones in the region based on radiometric information, being the uranium-rich albitite regions characterized by high counts of the three radioactive elements. We found that the Lagoa Real Intrusive Suite formed by uraniferous albitites, not only presented high concentrations of uranium (almost 7 ppm) but also high concentrations of potassium (just over 4%) and thorium (almost 50 ppm), thus being the most important region for mining activities.

Key words: Uranium, Thorium, Potassium, Radiometric Method, Lagoa Real

1. INTRODUCTION

Radiometry is based on the study of radioactive energy transfer in the form of particles or electromagnetic radiation that some unstable isotopes can emit. They can be present in numerous minerals, such as uranium (U), thorium (Th), and potassium (K), which are the most appropriate for the study of rocks [1].

The contents of these isotopes can vary according to the rock and layers. They are able to provide complementary information about the chemical characteristics of the rock, and then gamma spectrometry is the method used to detect the gamma rays from these radioactive isotopes [2].

Uranium is one of the most common isotopes; it was discovered in the 17th century in Germany by Klaproth and can be explored through the following ores: Uraninite, euxenite, carnotite, brannerite, torbenitee, and coffinite.

In 1979, strong uranium radiometric anomalies obtained in the Uranium Province of Lagoa Real made it possible to carry out the São Timóteo gamma-spectrometric and magnetic survey, which confirmed the existence of a series of occurrences of uranium [3].

The distribution of uranium mineralization and its formation conditions make the Province of Lagoa Real a great example of economic concentration of uranium, occurring mainly in the form of uraninite (U_3O_8) [4]. Thus, it is intended to use the gamma spectrometry method and thus obtain the mapping of radiometric concentrations of Uranium, Thorium, and Potassium in the uranium province of Lagoa Real, which is an area of great economic interest and with uranium reserves in operation.

Therefore, this work is organized as follows: Section II presents the characteristics of the study area, divided into three stages: Description of the municipality, geology, and topography of the region; Section III describes the radiometric method; Section IV presents the processing and interpretation of the data obtained for each radioactive isotope; and, finally, Section V presents the final considerations.

2. CHARACTERISTICS OF THE STUDY AREA

2.1. Municipality Description

The study area is the Lagoa Real Uranium Province, which is located in the south-central region of the state of Bahia, in the central part of the São Francisco Craton (Figure 1). According to Amorim *et al.* (2017) [5], it is the most important uranium reserve in Brazil, constituting the main uranium ore extraction site in activity in South America. It is inserted in the municipalities of Caetité and Lagoa Real and is 620 km from Salvador [6]. According to Nogueira (2018) [7], Nuclear Industries of Brazil (INB) operates in the uranium production chain, from mining to fuel production.

According to Alves (2005) [9], the process of implanting the Mining-Industrial Uraniferous Complex of Lagoa Real was developed in four stages. In the first phase, it occurred the discovery of the ore and the beginning of research activities between 1976 and 1985.

The second phase, which took place between 1986 and 1994, was linked to political decisions, characterized as a moment of uncertainty in relation to the Brazilian Nuclear Program. This period also made

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it possible to better understand the routine of the city and rural communities to be compensated for the installation of the Lagoa Real Project.

The third phase, from 1995 to 2000, coincides with the restructuring process of INB and it is characterized by the resumption of activities related to the nuclear issue in Brazil, specifically in Caetité, with resumption of work aimed at the implementation of the Lagoa Real Project.

The fourth phase takes place from the year 2000 until the present moment, when the installation work for the Uraniferous Complex is completed (Figure 2), occurring the inauguration, experimental tests and commercial operation of the company.

2.2. Geology of the Region

The geology of the uranium province of Lagoa Real is composed of metamorphic rocks, notably albitite, microcline and epidosite, amphibolite, and biotite [11]. The uranium mineralizations associated with geologic bodies of lenticular albitite that is located along shear zones that occur in the gneisses of the Lagoa Real Complex, from Arqueano. In this complex porphyritic granitic bodies, called São Timóteo granite, are also intruded, also affected by shear zones that host mineralized albitites, as shown in Figure 3.

Figure 1: Uranium Province of Lagoa Real [8]

NQdl - Debris-laterite coverings (<23.5 Ma): Sand with levels of clay and gravel and laterite crust.

PP4γl1 - Anorogenic Granitoids Suite Intrusive Lagoa Real (1800-1600 Ma): Hornblende-biotite, orthognaisse and quartz (1746-1724 Ma U-Pb).

PP4γl2 - Lagoa Real Intrusive Suite (1800-1600 Ma): Albitite with garnet, amphibole, and pyroxene, sometimes uraniferous (1744 Ma U-Pb, 961 Ma U-Pb, 487 Ma U-Pb).

PP4ylt - Lagoa Real Intrusive Suite (1800-1600 Ma): São Timóteo Granite: Biotite, hornblende, and quartz (1746-1724 Ma U-Pb).

PP4αrr - Paraguaçu Group (1800-1600 Ma): Rio dos Remédios Formation: Metarriolite (1752-1748 Ma U-Pb, 540 Ma U-Pb).

PP3γ4Pu - Late to Post-Tectonic Granitoids (2050-1800 Ma): Umburanas (2049 MaPb-Pb), Iguatemi (2030 Ma Rb-Sr) and Espírito Santo (2012 Ma Pb-Pb): Granodiorite and granite, lightly foliated.

A3po - Paramirim Complex (3200-2800 Ma): Orthogneiss, with remains of supracrustal rocks (2765 Ma Rb-Sr).

A34iu – Greenstone Belt from Ibitira-Ubiraçaba (3200-2500 Ma): Banded gneiss, quartzite, calcisilitic rock, amphibolite, iron formation, marble, and ultramafic shale.

A2gm - Gavião Complex (3600-3200 Ma): Migmatic orthognaisse (3300 Ma Pb-Pb).

*2.3. **Topography of the Region***

The topographic map of the Lagoa Real region was prepared using satellite data from the TOPEX V19.1 model. The relief of the region is shown in Figures 4 and 5.

The altitude varied from 500m to close to 1100m. The lowest region is Lagoa Real, in the southeast of the map, and the highest elevations are

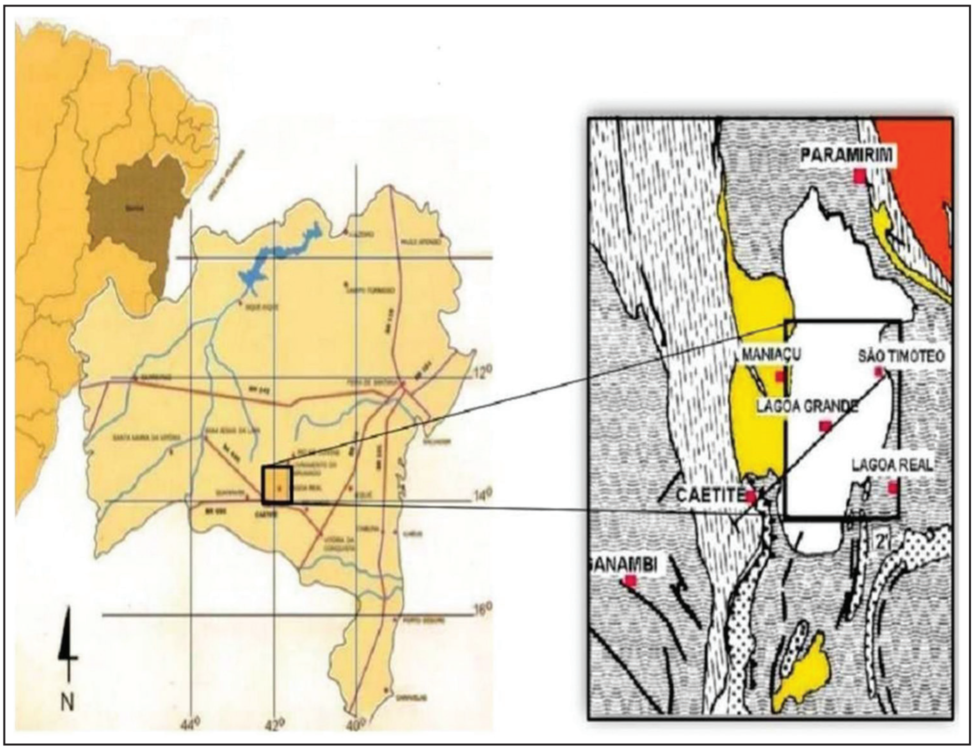

Figure 2: Aerial view of the uranium concentration facilities - Caetité Plant (Lagoa Real - BA) [10].

the region of Maniaçu, in the northwest and the north of São Timóteo, in the northeast of the map.

3. RADIOMETRIC METHOD

3.1. *Materials and Equipment*

According to Pinheiros and Crivelaro (2017) [13], the radiometric method or gamma-spectrometry is used to measure the intensity of radiation emitted by the elements U, K, and Th found in the rocks. Being widely used in geological mapping, because different rocks are characterized according to the radioactivity they present, in the same way, it can be used in the anomalous imbalances of the elements U, Th and K.

In the aerial surveys (Figure 6), the equipment is transported by small planes (as type DC-3 or Bandeirantes), ultra-light and helicopters or by means of artificial satellites and aircrafts. In some cases, sensors and transmitters can be installed on the aircraft or on a trailer (bird), thus avoiding inferences from the aircraft itself. However, the recorders are stored inside the aircraft [14].

Also, according to Barbosa (2003) [14], the aerial survey is characterized by the low cost and speed with which the results are obtained. In a single pass, simultaneous measurements can be made with more than one geophysical method. In this sense, Telles and Rabelo (2013) [15] add that the aerial survey is a non-intrusive method; it does not cause damage to the environment; it reaches coverage of large areas, considerably reducing the costs of regional surveys; and surface permissions are not required to access and open land in the field as environmental licenses. This data can be collected in remote, rugged areas, or with dense vegetation too.

However, according to Gonçalves (2008) [1], its disadvantage is the attenuation of anomalous sources close to the surface, making its application in mineral exploration limited. Gonçalves (2008) [1] points out that to convert the count rate observed per time unit into concentrations of radioelements on the earth's surface, it is important that the spectral windows of the total count, of Potassium, Uranium, and Thorium go through a large sequence of corrections.

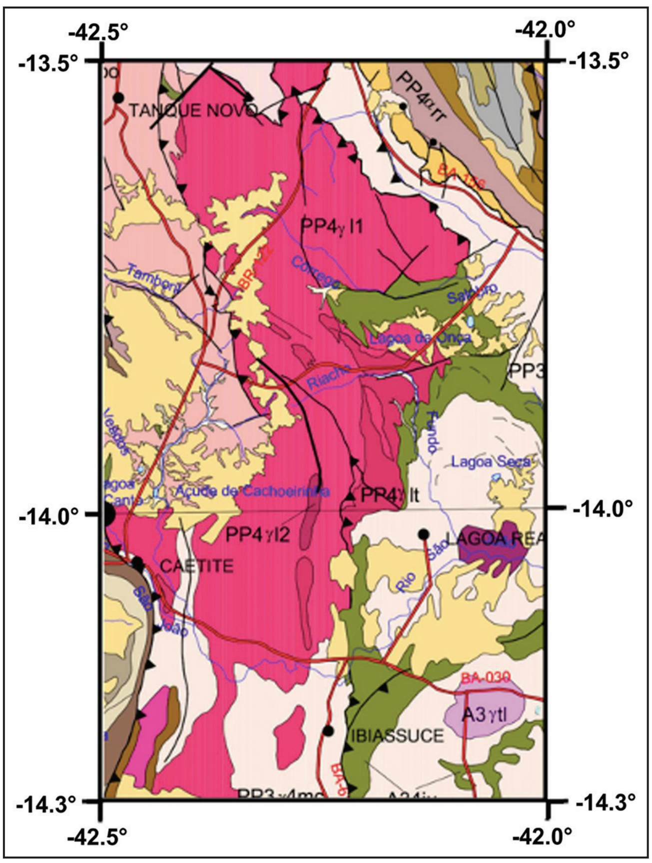

Figure 3: Geological map of the Lagoa Real region – 2003 [12].

3.2. *Geochemistry of Radioelements*

According to Bastos (2008) [16], all rocks are radioactive at different levels. The most abundant natural radio elements on the earth's surface are Potassium (40K), Thorium (232Th), and Uranium (238U). However, some studies, according to Ferreira (2013) [17], show that there are concentrations of radio elements in several types of rocks, in general, there is a wide range of concentration values in the same type of rock. The natural radioactivity of rocks varies according to their nature. In general, higher concentrations are common in igneous (granitic) rocks in relation to sedimentary and metamorphic rocks [18].

According to Matolin (1984) [19], the contents of radioactive elements in accessory minerals are controlled by the chemical composition of the magmas and conditions of magmatic differentiation. During the crystallization process of the magmas, the concentrations of the radio elements uranium and thorium are very low. However, in the last stages of magmatic differentiation, stages responsible for the development of acidic rocks, the concentrations of the elements become high, thus the radioactivity of the rocks can increase with the acidity of the magmas, as shown in Table 1.

As for sedimentary rocks, radioactivity will depend on the composition of the material subjected to sedimentation. Its radioactivity is related to the material that was deposited. Uranium mobility and thorium insolubility are important factors in sedimentary rocks [20]. Table 2 shows the concentration of K, U, and Th in sedimentary rocks.

In metamorphic rocks, the content of uranium, thorium, and potassium is the result of original contents of the material extracted from igneous and sedimentary rocks. They are altered by metamorphic processes. The content is adsorbed or reduced according to the degree of metamorphic transformation. In addition, the amount of radioactive elements decreases as metamorphism grows [18]. Table 3 shows the concentration of Thorium (Th), Uranium (U), and Potassium (K) in metamorphic rocks.

4. DATA PROCESSING AND INTERPRETATION

The data obtained from the São Timóteo project constitute a wide range of magneto metric and gamma-spectrometric data. Data processing

Table 1: Concentration of K, U and Th in igneous rocks [20]

Rock	K (%)	U (ppm)	Th (ppm)
Acidic	3.34	3.5	18.0
Intermediate	2.31	1.8	7.0
Basic	0.83	0.5	3.0
Ultrabasic	0.03	0.003	0.005

U: Uranium, Th: Thorium, K: Potassium

Table 2: Concentration of K, U, and Th in sedimentary rocks [20]

Rock	K (%)	U (ppm)	Th(ppm)
Brochures and Clays	2.7	4.0	11.0
Sandstones	1.2	3.0	10.0
Limestone's	0.3	1.4	1.8

U: Uranium, Th: Thorium, K: Potassium

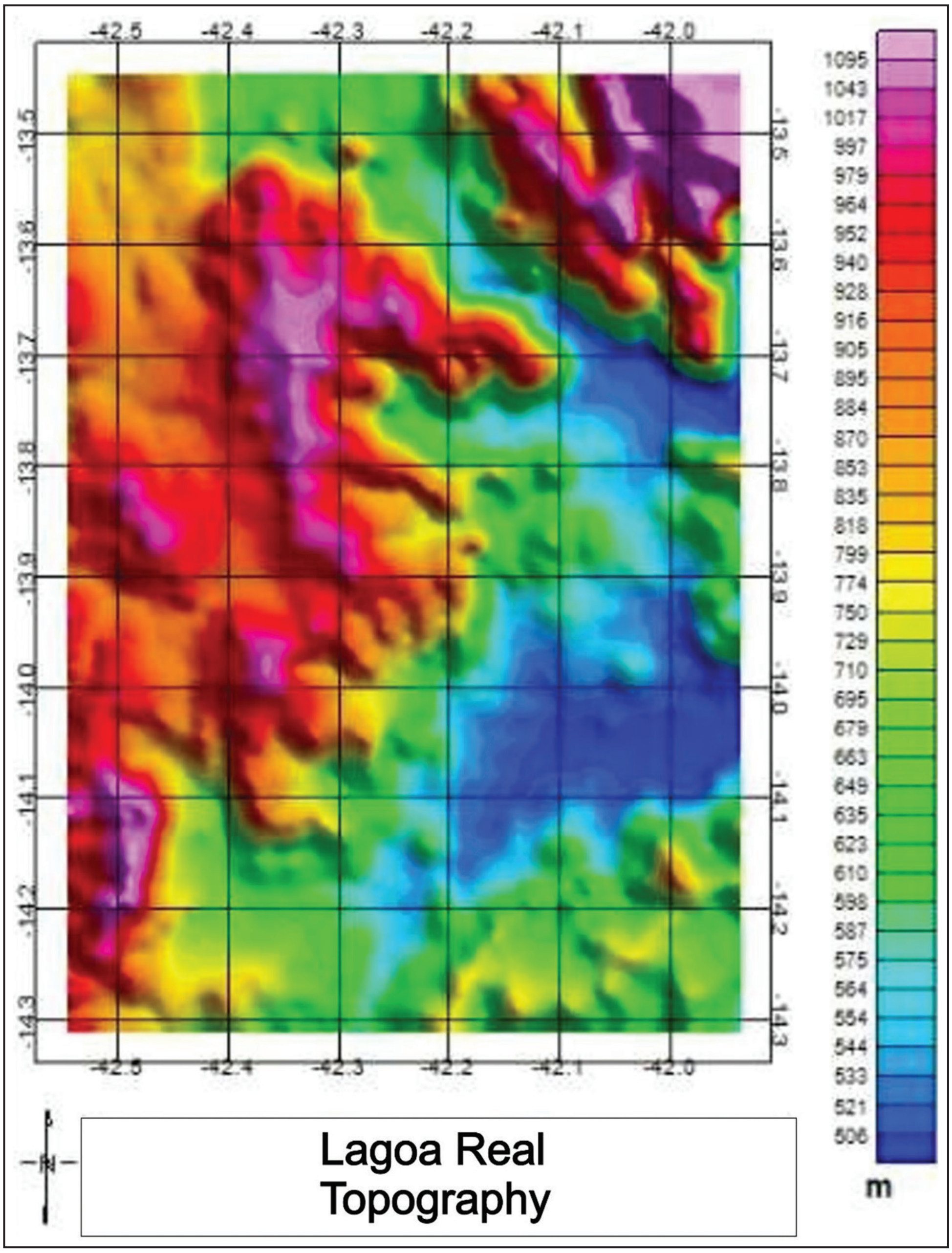

Figure 4: Topographic map of Lagoa Real region.

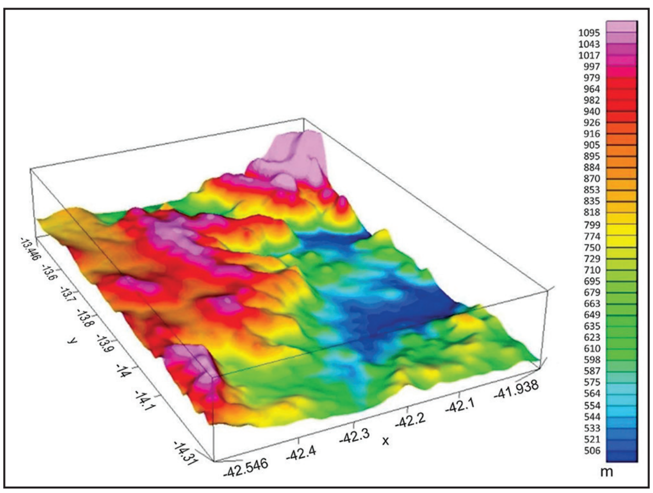

Figure 5: Topographic map of the Lagoa Real region (3D view).

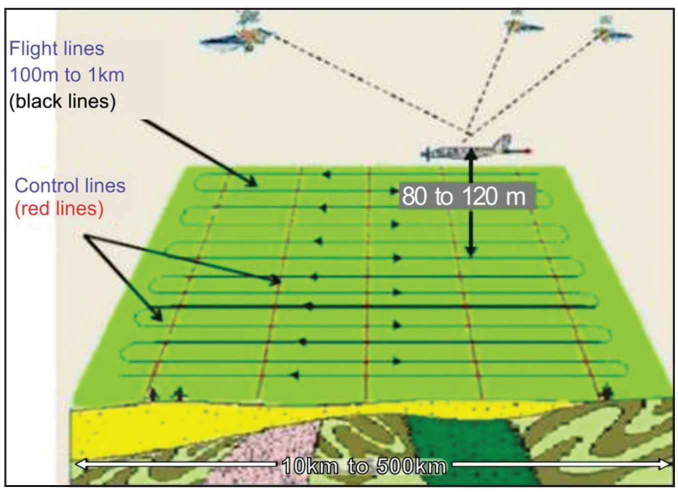

Figure 6: Schematic example for obtaining data by aerial survey [15].

was performed using the OASIS/MONTAJ software. The data were obtained with spacing between measurement profiles (line) of 500 m and direction of the measurement lines in E-W. The sampling interval was 1 s (approximately 60 m).

The gamma-spectrometer used was the Exploranium DIGRS-3001 with a volume of the detector crystals of 1017.87 cubic inches (thallium-activated sodium iodide crystals). The radiometric data were calibrated and corrected, and the concentrations were calculated through the BARMP - Brazilian Airborne Radiometric Mapping Project, carried out in partnership with CPRM - Geological Service of Brazil, and the Canadian firm PGW - Paterson, Grant and Watson. The data were then processed using a 125-m cell and minimal curvature interpolation.

4.1. Thorium Count

The thorium concentration map was made according to Figure 7. The map corresponds to the radioactivity energy range between 2.41 MeV and 2.81 MeV. The concentration varied between 3.54 ppm and 48.85 ppm.

4.2. Uranium Count

The uranium concentration map was made according to Figure 8. The map corresponds to the radioactivity energy range between 1.66

Table 3: Concentration of K, U, and Th in metamorphic rocks [20]

Rock	K (%)	U (ppm)	Th (ppm)
Amphibolite's	0.7	1.0	4.0
Gneisses	2.0	1.6	8.0
Schist	2.5	4.1	13.5
Marbles	0.4	1.1	1.8

U: Uranium, Th: Thorium, K: Potassium

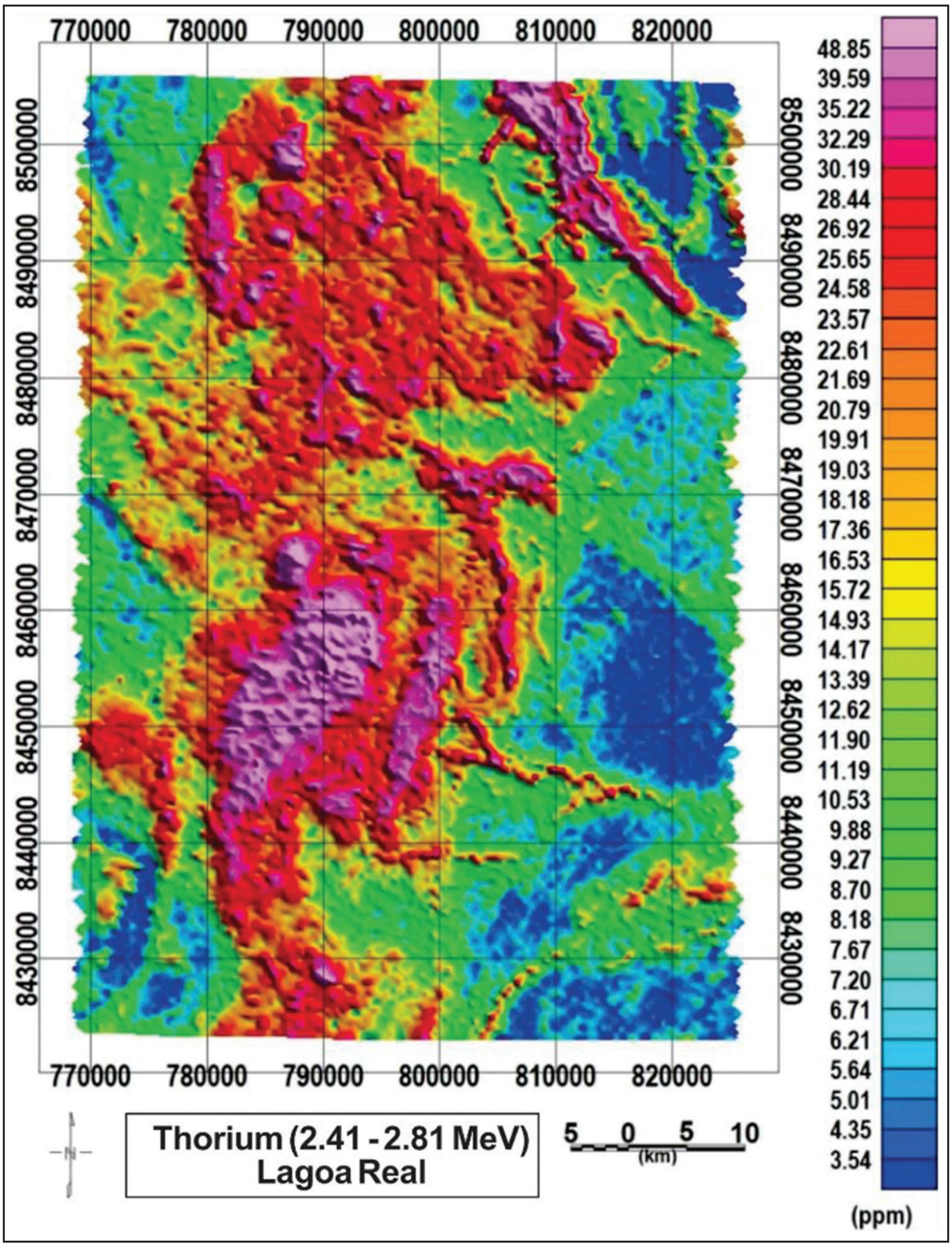

Figure 7: Thorium map.

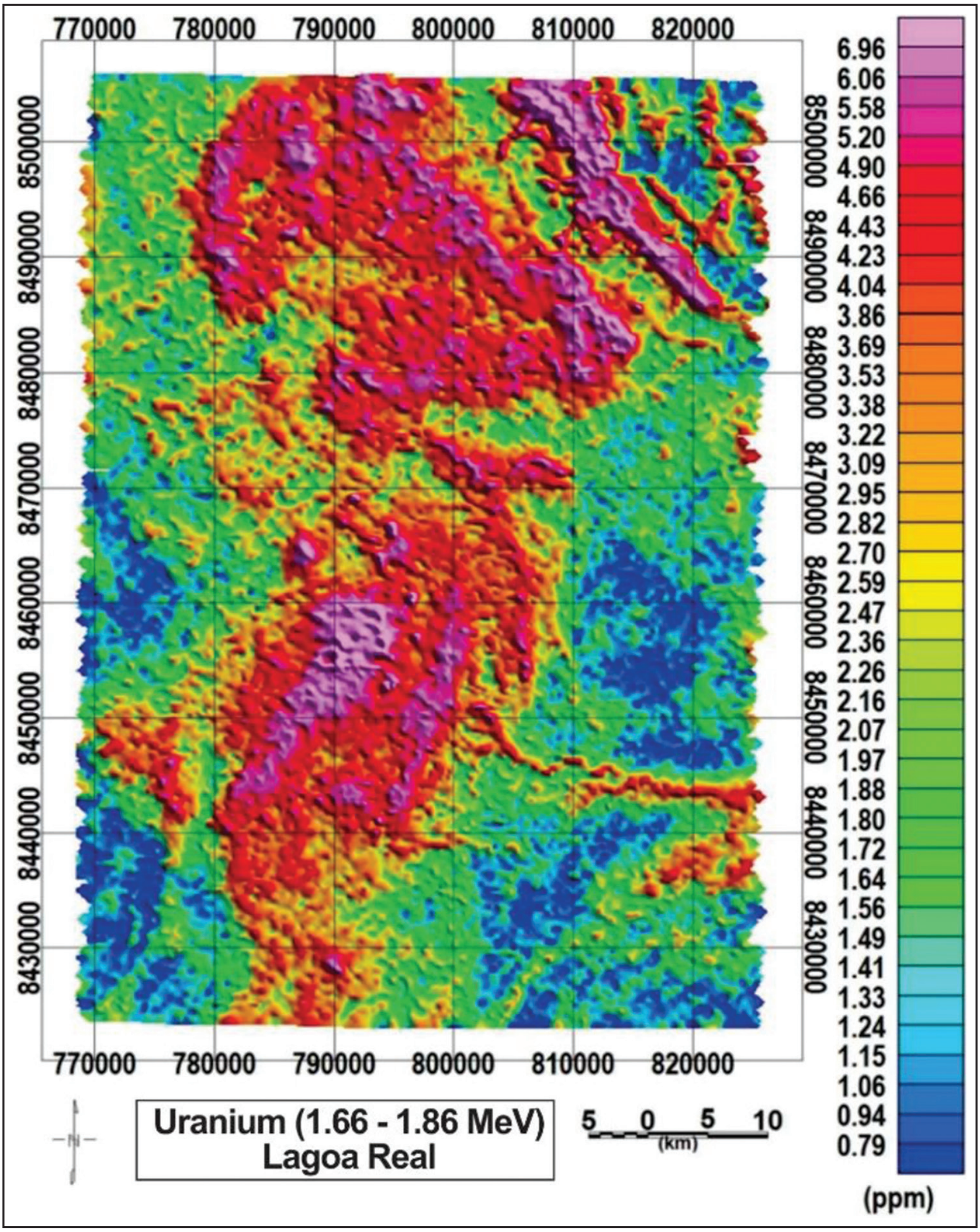

Figure 8: Uranium map.

MeV and 1.86 MeV. The concentration varied between 0.79 ppm and 6.96 ppm.

4.3. Potassium Count

The potassium concentration map was made according to Figure 9. The map corresponds to the radioactivity energy range between 1.37 MeV and 1.57 MeV. The concentration varied between 0.33% and 4.09%.

4.4. Total Count

The total count map was made according to Figure 10. The map corresponds to the radioactivity energy range between 0.41 MeV and 2.81 MeV. The count varied between 1.64 uR/h and 16.14 uR/h.

4.4. Ternary Map

The ternary map was made according to Figure 11. The map corresponds to the relative concentration of the radio elements thorium, potassium,

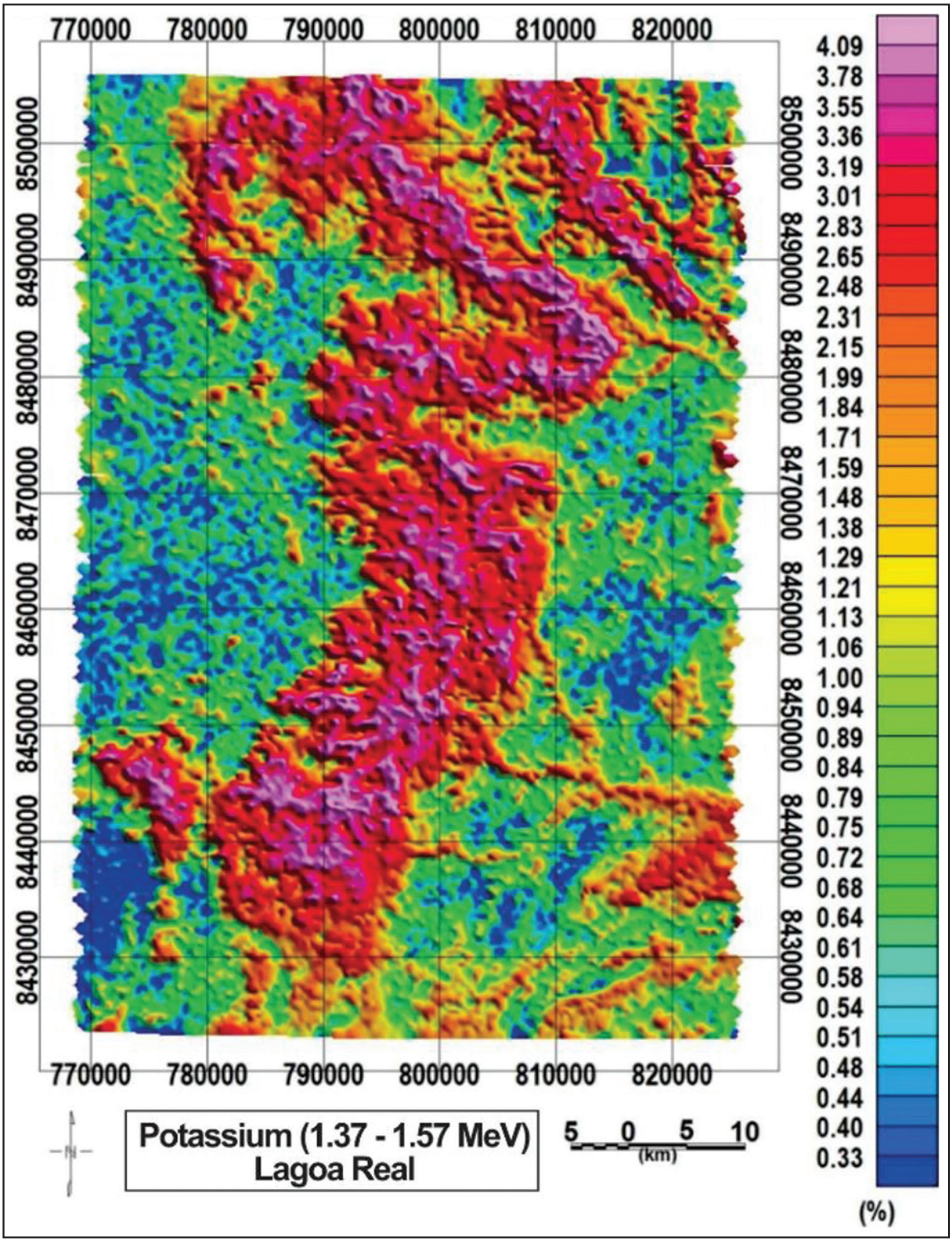

Figure 9: Potassium count.

and uranium. The CMY color standard (Cyan, Magenta, and Yellow) was used, with cyan for potassium, magenta for thorium and yellow for uranium. For intermediate colors we have: Green (potassium and uranium), Blue (potassium and thorium), and Red (thorium and uranium). In addition, the regions in black correspond to high counts of the three elements and the regions in white correspond to low counts of the three elements.

The comparing of the geological map of Figure 3 and the topographic maps of Figures 4 and 5 with the radiometric maps of Figures 7-11 shows that the regions with the highest concentrations of radio elements are those with the highest altitudes located in the central and northwest range of the map.

The regions that presented the highest concentrations of radioelements are the units Lagoa Real Intrusive Suite composed predominantly of

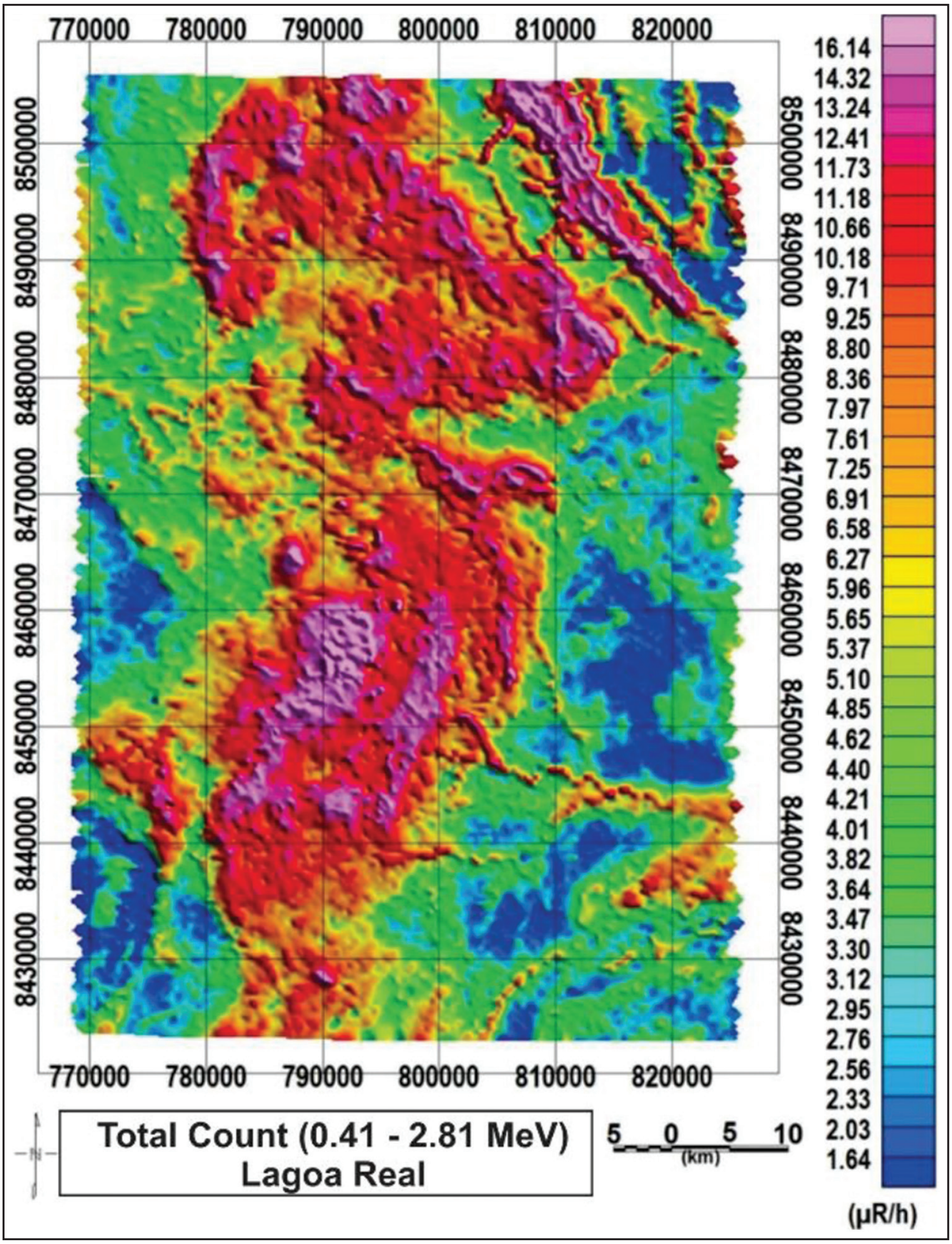

Figure 10: Total counting map.

granites and gneisses, in addition to the Paraguaçu Group in the Rios dos Remédios formation composed of metarriolites.

The regions that showed the lowest concentrations of radioelements are the lateritic coverings formed by sands, clays, and gravel, in addition to the Paramirim Complex, Greenstone Belt and Gavião Complex composed of gneisses, remains of crustal rocks, quartzites, schists, and marbles.

As for the predominance of radio elements, the lateritic coverings and the Paramirim Complex showed a predominance of Thorium, the Lagoa Real Intrusive Suite and the Paraguaçu Group showed high concentrations of the three radio elements and the other regions with a predominance of potassium and uranium.

Finally, the PP4γI2 unit of the Lagoa Real Intrusive Suite formed by uraniferous albitites is economically the most important region due to the exploitation of uranium. In this region, not only it occurred high concentrations of uranium (almost 7 ppm) but also it occurred high concentrations of potassium (just over 4%) and thorium (almost 50 ppm).

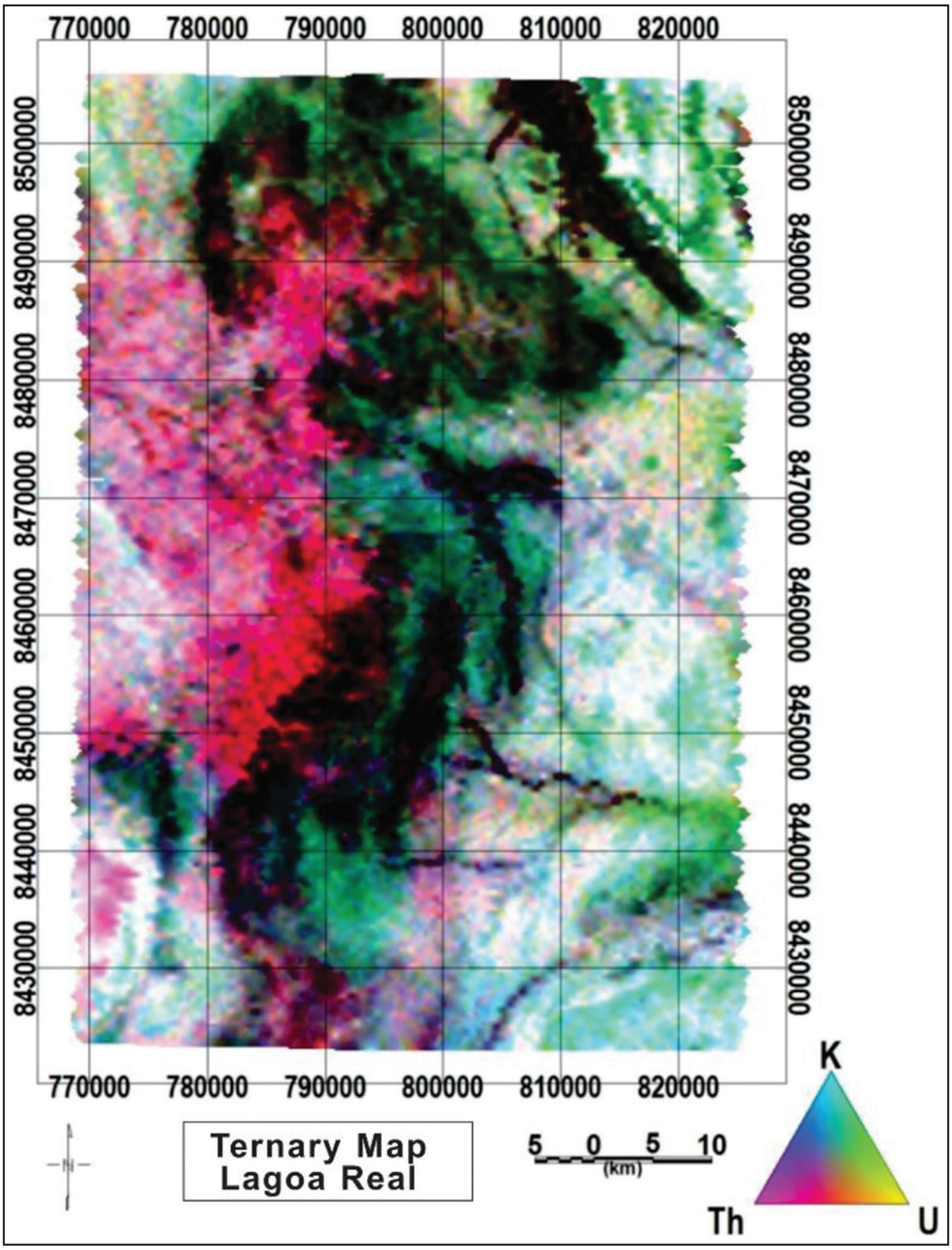

Figure 11: Ternary map.

5. CONCLUSION

In this work, the mapping of Uranium, Thorium, Potassium concentration and total count of the Lagoa Real Uraniferous Province were carried out based on gamma radiometric data from the São Timóteo project through the large database in.gbd format.

By means of Geosoft's Oasis Montaj software, maps of uranium, thorium, potassium, total count, and ternary were made. The maps were compared with the geological map and with the topographic map built using data from the Topex V19.1 model.

This mapping made it possible to characterize the subsurface geological structures associated with uranium mineralization zones in the region based on radiometric information. The uranium-rich albitite regions are characterized by high counts of the three radio elements.

For future studies, an on-site visit with photographs of the area and GPS marking is suggested. Thus, the photographs obtained from regions with mining activity could be correlated with the maps obtained, providing more important information. In addition, a literature review survey on the current outlook for uranium mining and the use of nuclear fuel in Brazil is suggested.

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