Gamma-ray spectrometry signatures of alkaline rocks from the Ponta Grossa Arch, southern Brazil

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Abstract

We present airborne gamma-ray spectrometry signatures of some igneous suites from the Ponta Grossa Arch Alkaline Province (southern Brazil), namely: Bairro da Cruz, Banhadão, Itapirapuã Nepheline syenite, Barra do Itapirapuã Carbonatite, Barra do Teixeira Phonolite, and Mato Preto and Tunas complexes. Gamma-ray spectrometric methods involved analyses of basic, ternary, and ratio maps, thorium-normalized parameters, and sampled data points radioelement concentrations. The results allowed us to verify that all complexes were mainly enriched in eTh. Carbonatite bodies showed the highest contents of eTh and eU. Our findings were consistent with radiometric responses of alkaline bodies and impact the understanding of alkaline provinces in Brazil.

Introduction

The Ponta Grossa Arch (PGA) is an uplifted domain located in southern Brazil (Fig. 1). This arch hosts both alkaline and carbonatite-alkaline intrusions and it was labeled Ponta Grossa Arch Alkaline Province (PGAAP) by Almeida (1983). Most of this province is situated between the southern parts of the Guapiara and São Jerônimo-Curiúva magnetic lineaments (Ferreira 1982). Alkaline intrusions have been recognized and detailed in different scales by airborne gamma-ray spectrometry surveys. These surveys contribute to a variety of geological and geophysical interpretations, such as mapping of bedrocks and mineral exploration (Airo 2015), as well as the discovery of uranium deposits in alkaline igneous complexes. Alkaline rocks tend to enrich in thorium (eTh), which forms complex ions with sulfides, carbonates, and phosphates. Furthermore, carbonatitic-alkalic complexes may show potential for rare earth elements (REE), niobium, and vermiculite mineralizations. Marangoni and Mantovani (2013) characterized the state-of-the-art magnetic and gravity signatures in the PGAAP. However, these authors have not reported gamma-ray signatures of the bodies from this alkaline province. High-resolution airborne gamma-ray spectrometry datasets (flight lines spaced around 0.5 km) were analyzed to assess the pattern of anomalies over the study area and then comparing these with previous studies.

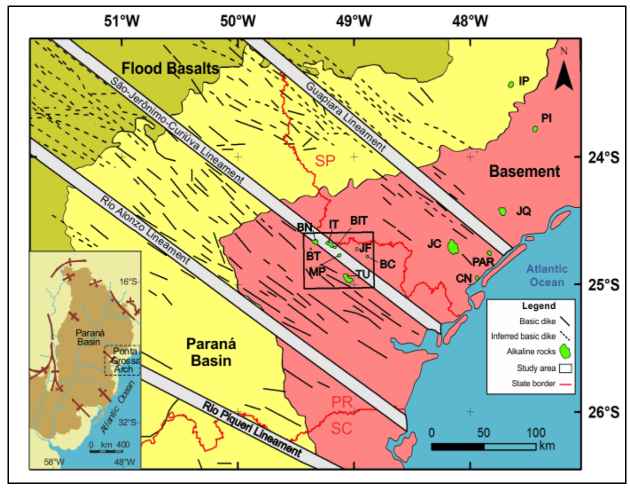

Figure 1 - Sketch map of the Ponta Grossa Arch Alkaline Province (modified from Ruberti et al. 2005; Gomes et al. 2018). Alkaline complexes: Bairro da Cruz (BC), Barra do Itapirapuã (BIT), Banhadão (BN), Barra do Teixeira (BT), Cananéia (CN), Ipanema (IP), Itapirapuã (IT), Jacupiranga (JC), José Fernandes (JF), Juquiá (JQ), Mato Preto (MP), Pariquera-Açu (PAR), Piedade (PI), and Tunas (TU). States: São Paulo (SP), Paraná (PR), and Santa Catarina (SC). See geological context in Silva and Ferreira (2021).

Material and Methods

The study area was delimited by UTM zone 22J coordinates 655,000 m - 720,000 m and 7,280,000 m - 7,230,000 m, comprising partial regions from the geological maps of Cerro Azul (Brumatti and Almeida 2014) and Apiaí (Morais et al. 2012) (Figs. 1 and 2). These 1:100,000-scale maps were used to discuss the geophysical data in association with the mapped geology. Gamma-ray spectrometric data were provided by the Geological Survey of Brazil - CPRM (2011) from the Paraná-Santa Catarina Project (PR-SC). North-south oriented flight lines were spaced 500 m apart. The data were acquired at a terrain clearance of 100 m. The radiometric data were interpolated onto a 100 m grid cell-size, which represents 1/5 of the spacing between lines, using the minimum curvature algorithm. Basic grids (K, eTh, and eU) were corrected following the procedure of Ferreira et al. (2009) where each radioactive element received a constant to keep its minimum value to 0.01 and, therefore, avoiding divisions by values equal or below to zero when ratioing. The constants added to the K, eTh, and eU grids were 1.05 %, 1.22 ppm, and 2.39 ppm, respectively. A ternary R-K, G-eTh, B-eU image was also generated for the study area. Fourteen ratio maps were generated (see maps in Silva and Ferreira, 2021). In addition, the parameters thorium-normalized potassium (KD), thorium-normalized uranium (UD), and DRAD (Saunders et al. 1994) were also implemented to evaluate the anomalies of potassium and equivalent uranium when they are normalized in relation to eTh (see Silva and Ferreira, 2021). The minimum, average, and maximum levels of K, eTh, and eU of each intrusion in the study area were determined from the gridded data and plotted in box-plot charts. Radioelements concentrations for each sampled data point inside complexes' boundaries were illustrated in normalized ternary diagrams created in the TriPlot software and later refined in the origin suite to identify trends in K, eTh, and eU concentrations (see diagrams in Silva and Ferreira 2021). Also, stacked profiles (used to display more reliable data, i.e., with full spatial resolution, than a grid) containing the variables K, eU, and eTh from the PR-SC airborne survey flight lines were plotted along the mapped lithotypes for each intrusion to assess their absolute and relative levels.

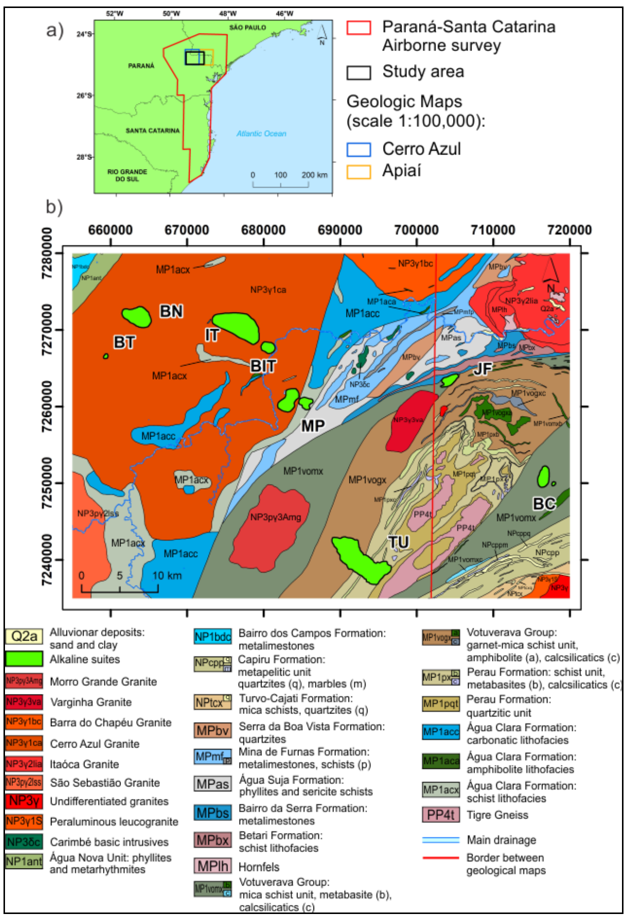

Figure 2 - Location of the study area within the airborne geophysical survey and geological maps used in this work (a). Simplified geological map for the study area based on Cerro Azul (Brumatti and Almeida 2014) and Apiaí (Morais et al. 2012) maps (b). Alkaline complexes: Bairro da Cruz (BC), Barra do Itapirapuã (BIT), Banhadão (BN), Barra do Teixeira (BT), Itapirapuã (IT), José Fernandes (JF), Mato Preto (MP), and Tunas (TU).

Results and Discussion

Radiometric Analysis

Figure 3 provides an overview of K (%), eTh (ppm), and eU (ppm) concentrations for each intrusion according to the data of the PR-SC project. What stands out in the box-plot charts is that eTh is the most abundant radioactive element for all suites, sometimes extrapolating values of 50 ppm. In addition, practically all the minimum, maximum and mean quantities of eU are higher than K ones. This radioelement has its highest concentration on the Mato Preto suite (5.07 %). Also, this intrusion has the highest average of potassium values (2.27 %). Overall, eU and K have lower concentrations in comparison with eTh. For example, there is a 20-fold increase in this radioelement averaged concentration compared to eU in the Barra do Itapirapuã Carbonatite. In addition, this intrusion displayed mean concentrations of K, eU, and eTh as follows: 0.54 %, 24.37 ppm, and 413.24 ppm, respectively. The higher values for eTh and eU, in particular eTh, support evidence from previous studies (e.g., Ford et al. 1988), which demonstrated that high values of both elements, especially eTh, are frequent in carbonatites and REE-bearing alkaline intrusions. For instance, Ford et al. (1988) reported values for the Allan Lake carbonatite (Canada), ranging from 1.4 - 3.5 %, 0.5 - 3.8 ppm, and 14.5 - 119.4 ppm for K, eU, and eTh, respectively. Similarly, the Mato Preto Complex has K concentrations situated in intervals of 0.08 to 5.07 %, eU in 2.43 - 27.23 ppm, and eTh in 21.76 - 443.49 ppm. This alkalic-carbonatitic suite showed the highest values of eTh, except for Barra do Itapirapuã. A possible suggestion for this is that while BIT is comprised in its majority of carbonatites, and thus frequently displaying large eTh values, MP has alkaline lithotypes in its configuration, lowering the average concentrations for that radioelement. Overall, whereas K and eU levels for the complexes studied in this work were consistent with one of the rock types defined by Galbraith and Saunders (1983), eTh for the same complex demonstrated to be higher than the average for these authors' classification. These findings may somewhat limit the creation of a generic system to characterize each complex. This is due to the fact that they are composed of different alkaline lithofacies in the majority of the cases and, therefore, display different radioelements levels according to their lithofacies composition.

Profile Analysis

Bairro da Cruz Complex

It can be seen that the radioelements levels from the Mica schists unit (Morais et al. 2012) start decreasing (K and eU) or remain stable (eTh) when entering in the BC Complex (Fig. 4). In this igneous intrusion, K and eTh increased their concentrations towards the body's central part. For the latter, its figure reached around 7 ppm when there was also a maximum of K concentration (i.e., 1.7 %) and remained constant until drops to over 5 ppm after 500 m approximately. Equivalent uranium has displayed some high and low peaks, but, in general, remained virtually stable. In the central part, where eTh kept constant, that radioelement reached its lowest values inside the igneous suite.

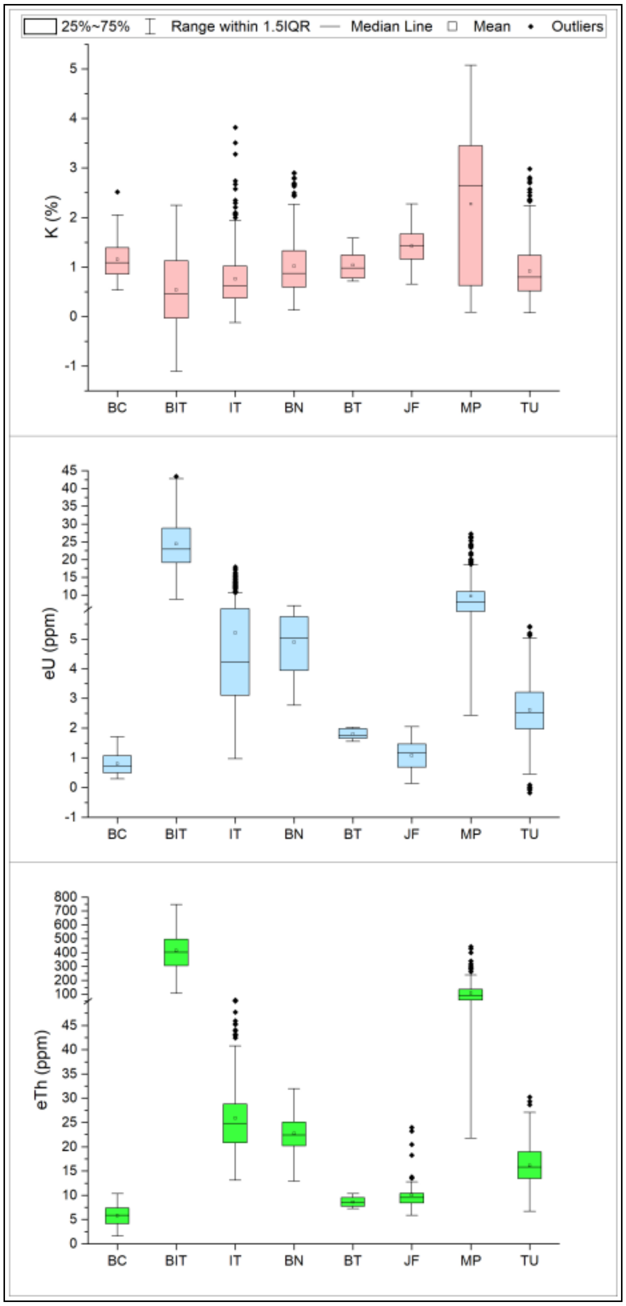

Figure 3 - Box-and-whisker plots of radiometric data from the airborne geophysical survey. IQR stands for interquartile range. Alkaline complexes: Bairro da Cruz (BC), Barra do Itapirapuã (BIT), Banhadão (BN), Barra do Teixeira (BT), Itapirapuã (IT), José Fernandes (JF, profile not showed), Mato Preto (MP), and Tunas (TU). Note that the eU and eTh plots have a scale break to improve readability since there are large differences between the high and low values of the data.

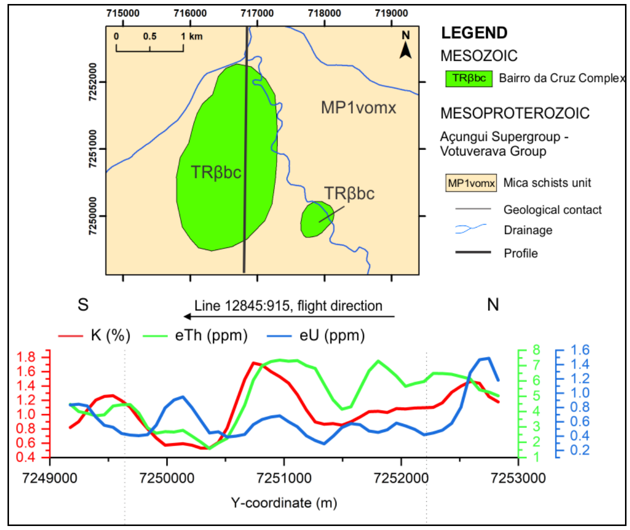

Figure 4 - Flight line profile for radioelements (K, eTh, and eU) from Bairro da Cruz Complex.

Banhadão Complex

The profile data for Banhadão Complex can be visualized in Figure 5. Potassium distribution has displayed levels between 0.6 and 2.2 %. The highest concentration of this radioelement is located between the Phlogopite melteigite (Kλbam) and Pink nepheline syenite (Kλbansr) units in the central part of Banhadão. The Sodalite syenite (Kλbass) unit showed the lowest values for K, eTh, and eU with 0.6 %, 18, and 4 ppm, respectively. Equivalent uranium values in the Banhadão Complex increased gradually from its southern part peaking between the Gray nepheline syenite (Kλbansc) and Pink nepheline syenite (Kλbansr) geological contact and then slowly decreasing until the Sodalite syenite (Kλbass) lithofacies. The figure for eTh is somewhat similar to the eU one, although it is more erratic with sharper increases and decreases in some points over the profile.

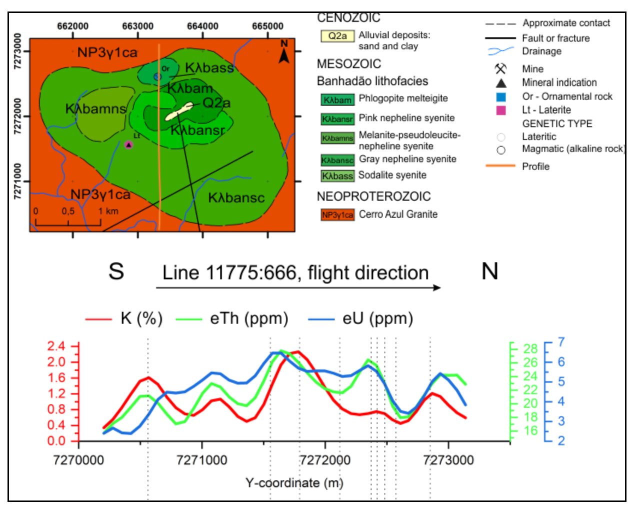

Figure 5 - Flight line profile for radioelements (K, eTh, and eU) from Banhadão Complex.

Itapirapuã Nepheline syenite

Figure 6 provides an overview of the radioelement concentrations in the flight line which has flown in the Itapirapuã syenite. Ranging intervals for this intrusion are: 0 - 3.75 % K, 20 - 37 ppm eTh, and 2 - 14 ppm eU. What is interesting about the data in this profile is that all radioelements have peaked in virtually the same Y-coordinate (eTh peaked some meters near the south of this coordinate), located in the center of the Itapirapuã Nepheline syenite. In addition, a local low near the northern part of the peak described above is observed for K, eTh, and eU then followed northward by a local high.

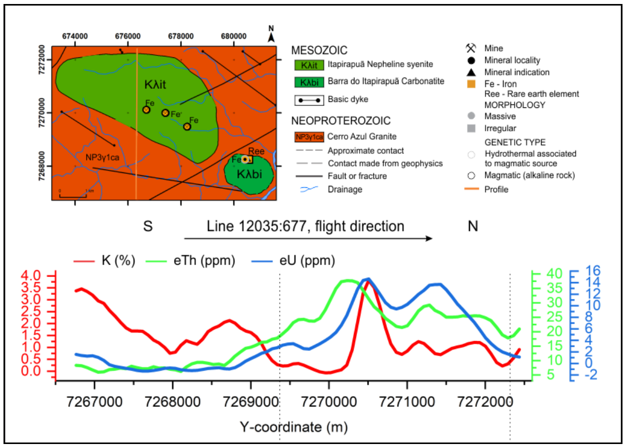

Figure 6 - Flight line profile for radioelements (K, eTh, and eU) from Itapirapuã Nepheline syenite.

Barra do Itapirapuã Carbonatite

This carbonatite body displayed higher concentrations of eU and eTh than its country rock (Fig. 7), i.e., Cerro Azul Granite. The maximum values of these radioelements for this intrusion are 45 ppm eU and 550 ppm eTh and they are located in the southernmost part of the BIT profile. These values then steadily drop towards the north of the profile. On the other hand, the opposite occurs for the potassium data. Its distribution starts decreasing when entering in the southern portion of the Barra do Itapirapuã, reaches a small high around 1.0 % and then plunges to near zero to start rising near the contact with Cerro Azul Granite. Then, this figure remains almost constant until rising above 3.0 % at the end of the profile.

Barra do Teixeira Phonolite

K distributions for the BT are situated between 0.25 and 1.75 % while eTh and eU figures range from 7 to 10 ppm and 1.5 to 2 ppm, respectively (Fig. 8). The southern part of the phonolite is characterized by showing higher values of eU while there is a decrease of K and eTh from the south to the central part of this body. There is a sharp rise of K along with eTh in the northern region of the Barra do Teixeira profile that continued into the Cerro Azul Granite. Overall, higher radioactive element concentrations are situated near the edges of the phonolite.

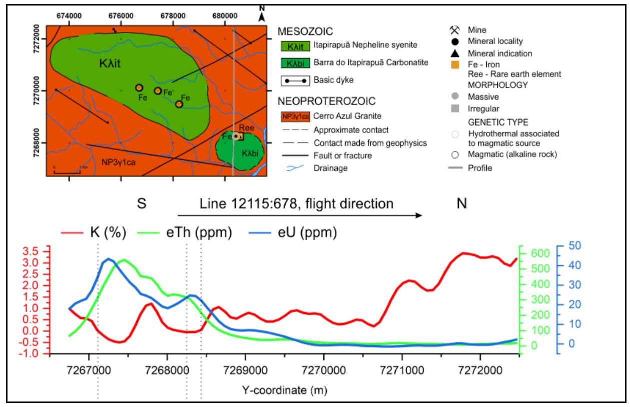

Figure 7 - Flight line profile for radioelements (K, eTh, and eU) from Barra do Itapirapuã Carbonatite.

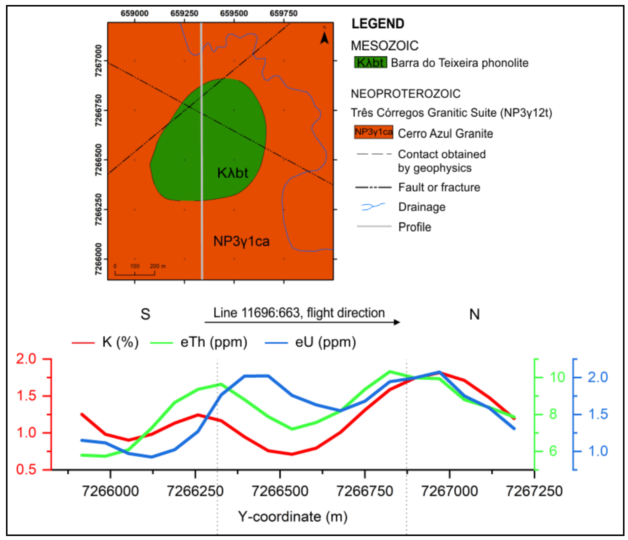

Figure 8 - Flight line profile for radioelements (K, eTh, and eU) from Barra do Teixeira Phonolite.

Mato Preto Complex

Two profiles are illustrated for the Mato Preto Complex, one for its western area (Fig. 9) and the other for its eastern counterpart (Fig. 10). The profile located on the Mato Preto western portion (Fig. 9) comprised K, eTh, and eU concentrations varying from 2.0 - 4.5 %, 50 - 325 ppm, and 2.5 - 27.5 ppm, respectively. The most remarkable result is that there is a steady increase northward of eTh and eU reaching their maximum concentrations in the carbonatite lithofacies (Kλmpc) while the lowest potassium levels are located over this eTh and eU maxima. This is in good agreement with the profile of the Barra do Itapirapuã carbonatite (Fig. 7), which showed a similar pattern for these radioelement distributions, i.e., high contents of eTh and eU with a low of potassium levels juxtaposed. The detection of different lithotypes in the MP complex may be only seen in the potassium profile, where there are some slight increases and decreases in its concentration.

The eastern portion of Mato Preto is comprised only by the undifferentiated alkaline rocks unit (KλmpI). Its profile (Fig. 10) has the highest concentrations of eTh and eU in comparison with its country rock, schists from Água Clara Formation. Registering around 225 ppm eTh and 10 ppm eU, these peaks are situated in the central-south area of the Mato Preto suite. Like its eastern counterpart, there is a potassium depletion (around 0.25 %) stacked in the same position of eTh and eU peaks. This response seems consonant with a carbonatite radiometric signature (i.e., eTh and eU highs and K lows with unusual values of eTh, above 100 ppm), hence indicating that the undifferentiated alkaline rocks unit (Kλmpi) could host carbonatite bodies.

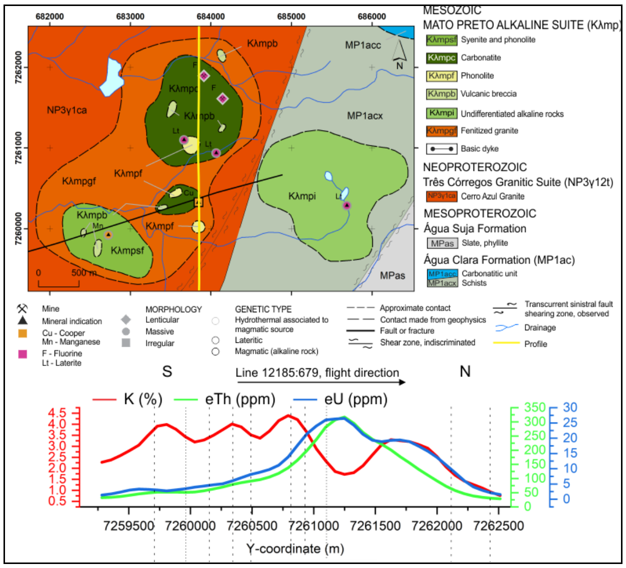

Figure 9 - Flight line profile (west) for radioelements (K, eTh, and eU) from Mato Preto Complex.

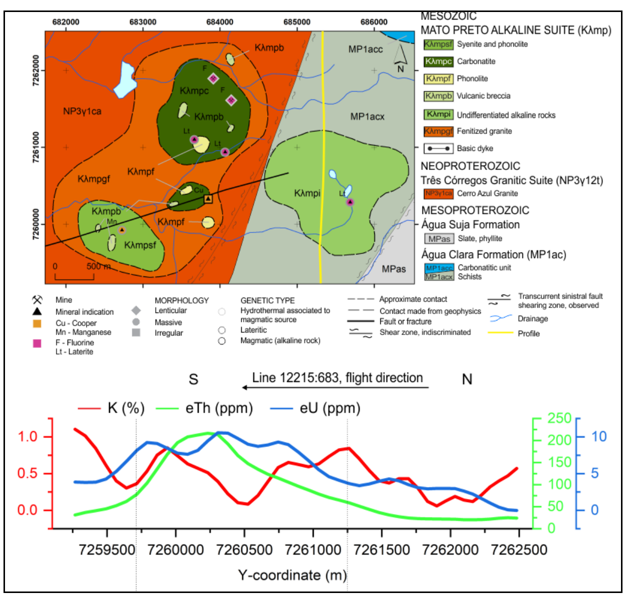

Figure 10 - Flight line profile (east) for radioelements (K, eTh, and eU) from Mato Preto Complex.

Tunas Complex

Both profiles from Tunas (Figs. 11 and 12) could be characterized as the most erratic series between the complexes studied in this work. They displayed a large variety of ups and downs alongside the radiometric data. This result may be explained by the fact that those profiles comprise different rock types, including quaternary deposits, and also by the abrupt changes observed in the digital terrain model data. This variation in the DTM could influence the geomorphic processes and thus the rock/soil responses of gamma-rays (Wilford et al. 1997). Profile 1 (Fig. 11) demonstrated the highest levels of eTh and eU inside the western Tunas Complex. These concentrations, approximately 22.5 and 5 ppm, respectively, are located on the syenite and alkaline syenite unit (Kλtns). This lithotype also carries the lowest quantities of K in the profile, i.e., almost 0.0 to 0.5 %. This radioelement increased in the Monzodiorite and diorite unit (Kλtnd), even though its concentration is lesser than in Tunas country rocks. Similar to Profile 1, eTh and eU top levels in Profile 2 (Fig. 12) are placed in the syenite and alkaline syenite (Kλtns) lithofacies. Equivalent thorium results are 14 ppm with a local low of around 9 ppm in the center of this unit while eU erratic increase from south to north peaking almost 3 ppm inside of Kλtns lithofacies. K quantities for Tunas eastern portion are somewhat higher, above 1.0 to 1.5 ppm, than in the western region. In addition, K concentrations in the syenite and alkaline syenite (Kλtns) lithofacies are higher than Tunas country rocks in the eastern profile, while the opposite is seen in the western profile (Fig. 11).

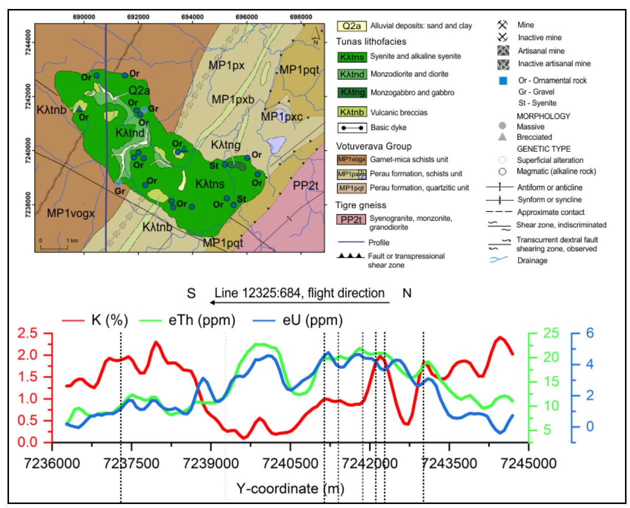

Figure 11 - Flight line profile 1 for radioelements (K, eTh, and eU) from Tunas Complex.

Conclusions

High-resolution airborne geophysical data provides a powerful component for geologic interpretation when access to their outcropped area is difficult. Prior works have not documented the gamma-ray spectrometry signatures of alkaline bodies in the Ponta Grossa Arch Alkaline Province (PGAAP). Our analyses displayed that these rocks are enriched in eTh in relation to eU and K, which supports other works regarding alkaline complexes. In addition, we found the radiometric data useful to distinguish complexes that host carbonatites from those that do not contain them since the alkaline-carbonatitic bodies' profile data showed coincidental eTh and eU highs and K lows in which the eTh values are above 100 ppm. More information on radiometric data, such as conducting small-scale ground geophysical surveys, would help us to establish a greater degree of accuracy on this matter. Most notably, this is the first study to our knowledge to investigate in a more detailed way the radiometric responses from alkaline bodies in the Ponta Grossa Arch, thus it has contributed to the understanding of geophysical signatures of alkaline provinces.

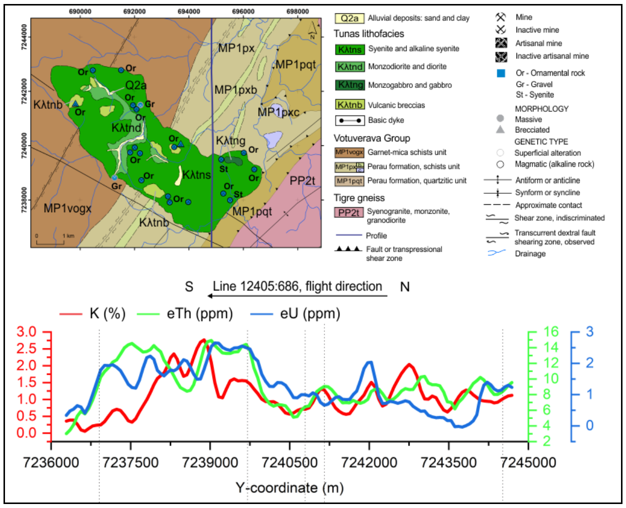

Figure 12 - Flight line profile 1 for radioelements (K, eTh, and eU) from Tunas Complex.

Acknowledgments

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