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URANIUM PROSPECTING IN NORTHEASTERN GOIÁS STATE, BRAZIL: MULTIPLE REGRESSION APPLIED TO AIRBORNE GEOPHYSICAL DATA

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ABSTRACT. Nuclebrás and Comissão Nacional de Energia Nuclear (CNEN) investigated northeastern Goiás State, Brazil, in the 1970s and 1980s to detect radioactive elements, when the Rio Preto and Campos Belos prospective uranium projects were undertaken. These projects identified an estimated 1,000 tons of U_3O_8, which was considered small and, therefore, search was interrupted in these areas. In 2006, an airborne geophysical survey covered these areas with gamma ray spectrometry and magnetometry data. Aerogeophysical data has been widely used in the direct detection of uranium mineralized bodies. However, in areas of great lithological variability, the determination of the anomalous values becomes difficult because uranium concentration is significantly influenced by the rock type. The objective of this study is to evaluate the multiple linear regression technique applied to the aerogeophysical data that cover the anomalous lithological units of uranium in northeastern Goiás, using the methodology proposed by Pires et al. (2010), to mitigate the influence of lithology on the uranium concentrations. The results demonstrate the effectiveness of the proposed methodology for the removal of lithological influences on the uranium levels, highlighted the known uranium occurrences in the region and identified new prospective targets for this radioelement.

Keywords: gamma ray spectrometry, magnetometry, anomaly enhancement, Ticunzal Formation, Aurumina Suite.

RESUMO. A região nordeste do Estado de Goiás foi investigada pela Nuclebrás e pela Comissão Nacional de Energia Nuclear (CNEN) nas décadas de 1970 e 1980 com vistas a detectar elementos radioativos, ocasião em que foram empreendidos os projetos prospectivos de urânio Rio Preto e Campos Belos. Tais projetos identificaram mineralizações uraníferas estimadas em cerca de 1.000 toneladas de U_3O_8, que foram consideradas de pequeno porte, portanto, foram interrompidos os trabalhos de pesquisa. Em 2006 foi executado um levantamento aerogeofísico que recobriu as áreas destes projetos com dados de gamaespectrometria e magnetometria. Dados aerogeofísicos têm sido amplamente utilizados na detecção direta de corpos mineralizados em urânio. Entretanto, a determinação de valores a serem considerados anômalos torna-se difícil para áreas de grande variabilidade litológica, pois a concentração de urânio é significativamente influenciada pelo tipo de rocha. O objetivo do presente trabalho é avaliar a técnica de regressão linear múltipla aplicada aos dados aerogeofísicos que recobrem as unidades litológicas anômalas em urânio no nordeste de Goiás, utilizando a metodologia proposta por Pires et al. (2010), para atenuar a influência litológica sobre as concentrações de urânio. O resultado demonstrou a eficácia da metodologia proposta na remoção de influências litológicas sobre os teores de urânio, como também realçou as ocorrências de urânio conhecidas na região e identificou novos alvos prospectivos para este radioelemento.

Palavras-chave: gamaespectrometria, magnetometria, realce de anomalias, Formação Ticunzal, Suíte Aurumina.

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INTRODUCTION

Prospecting for radioactive minerals peaked in the 1970s and 1980s in Brazil, a period in which several geophysical surveys were carried out, mainly by companies linked to the state monopoly of the nuclear power industry such as Brazilian Nuclear Enterprises (Empresas Nucleares Brasileiras) S.A. – Nuclebrás, nonexistent since 1988, and the National Nuclear Energy Commission (Comissão Nacional de Energia Nuclear) – CNEN. These efforts identified several radioactive minerals occurrences, especially uranium, scattered throughout the country. Some of them had significant economic potential, like the deposits of Poços de Caldas, Minas Gerais State; Lagoa Real, Bahia State; and Itataia, Ceará State.

CNEN and Nuclebrás, assisted by aerial surveys, identified in northeastern Goiás State (GO) significant uranium anomalies associated with metasedimentary rocks in Colinas do Sul, Cavalcante and Campos Belos. After initial probing, the prospects were considered small and, consequently, the work was suspended (Andrade et al., 1985). Currently, the global demand for uranium for purposes of generating electricity has grown, both due to increasing global energy demand and the search for fossil fuels alternatives. In this scenario, Brazil occupies a prominent position, owning the 6th largest uranium reserves in the world, even having prospected only a quarter of its territory (Gomes et al., 2003).

This paper proposes revisiting lithological units anomalous in uranium in northeastern Goiás, using the multiple linear regression technique, as proposed by Pires et al. (2010), to evaluate its effectiveness and identify new uranium targets, depending on the availability of new geophysical data for the region (Fig. 1).

Geological context

The region of interest is inserted into a mobile belt that comprises the Tocantins Structural Province (Almeida et al., 1977) and the Brasília Fold Belt – BFB. According to Fuck et al. (1994), BFB comprises two areas with distinct metamorphism and deformation patterns, the Internal and the External zones, in addition to Goiás Massif and Magmatic Arc. The External Zone, with green schist to amphibolite facies metamorphism, borders longitudinally the western boundary of the São Francisco Craton and comprises extensive Meso/Neoproterozoic metasedimentary covers, such as the Paranoá and Bambuí Groups, as well as basement exposures in its northern portion. A simplification of the geological context, adapted from Goiás State GIS (Moreira et al., 2008), is shown in Figure 2.

The known occurrences of uranium in northeastern Goiás (Andrade et al., 1985) are found in these basement exposures of northern BFB, composed by the Almas-Dianópolis Terrain and Paleoproterozoic metasedimentary covers such as Araí, Serra da Mesa, and Natividade Groups (Fig. 2). The Almas-Dianópolis Terrain in the region of interest was divided in three distinct geological units: the Ticunzal Formation (Marini et al., 1978), the peraluminous Aurumina Suite (Botelho et al., 1999), and the Goiás Stanniferous Province (Botelho, 1992). The Ticunzal Formation is the oldest unit, geochronologically, and is intruded by the Aurumina Suite with U/Pb ages between 2.27 and 2.02 Ga obtained in pegmatites (Sparrenberger & Tassinari, 1998). Both Ticunzal Formation and Aurumina Suite were intruded by Goiás Stanniferous Province granites, with ages from 1.77 to 1.58 Ga (Pimentel et al., 1999).

According to the available literature, uranium mineralizations occur mainly in Ticunzal Formation rocks (Andrade et al., 1985), and as subordinate, in Aurumina Suite rocks (Bonotto & Duarte, 2006). The Ticunzal Formation, with two units, consists predominantly of graphite schists, and also paragneisses and mica-schists in the lower unit, as well as quartz-schists and tourmaline-schists in the upper unit. The Aurumina Suite consists of granite, deformed peraluminous and, sometimes, mylonitic tonalites. In northeastern Goiás, analogous to Ticunzal Formation, these granites outcrop in the lower portions of the relief, typically in valleys bounded by the quartzite escarpments of the Araí Group.

Airborne geophysics in uranium prospecting

Uranium deposits are formed in almost all geological environments, from sedimentary and superficial, to diagenetic, volcanic, hydrothermal, metasomatic, plutonic, and even high-grade metamorphic (Dahlkamp, 1993). The geochemistry of uranium is mainly governed by its oxidation state. The highly mobile under oxidizing conditions uranyl ion (UO_2^{2+}), forms more than 40 different complexes with hydroxyl, carbonate, sulfate, chloride, phosphate, fluoride and silicate anions (Langmuir, 1978). In most deposits uranium precipitation arises from the interaction of oxidizing fluids rich in uranium complexes with reducing materials, especially those rich in carbon (Cuney, 2009).

The mineralizations may be composed of a wide range of minerals such as uraninite, uranothorite, uranothorianite and uranospherite, while in non-mineralized rocks uranium is present in the structure of minerals such as zircon, monazite and allanite. Its average concentration in the upper continental crust is 2.7 ppm. It is generally higher in acid and lower in basic rocks, and proportional to the silica content (Minty, 1997). Mafic igneous rocks have low average uranium content, usually below 2 ppm, while felsic igneous rocks have average content two or three

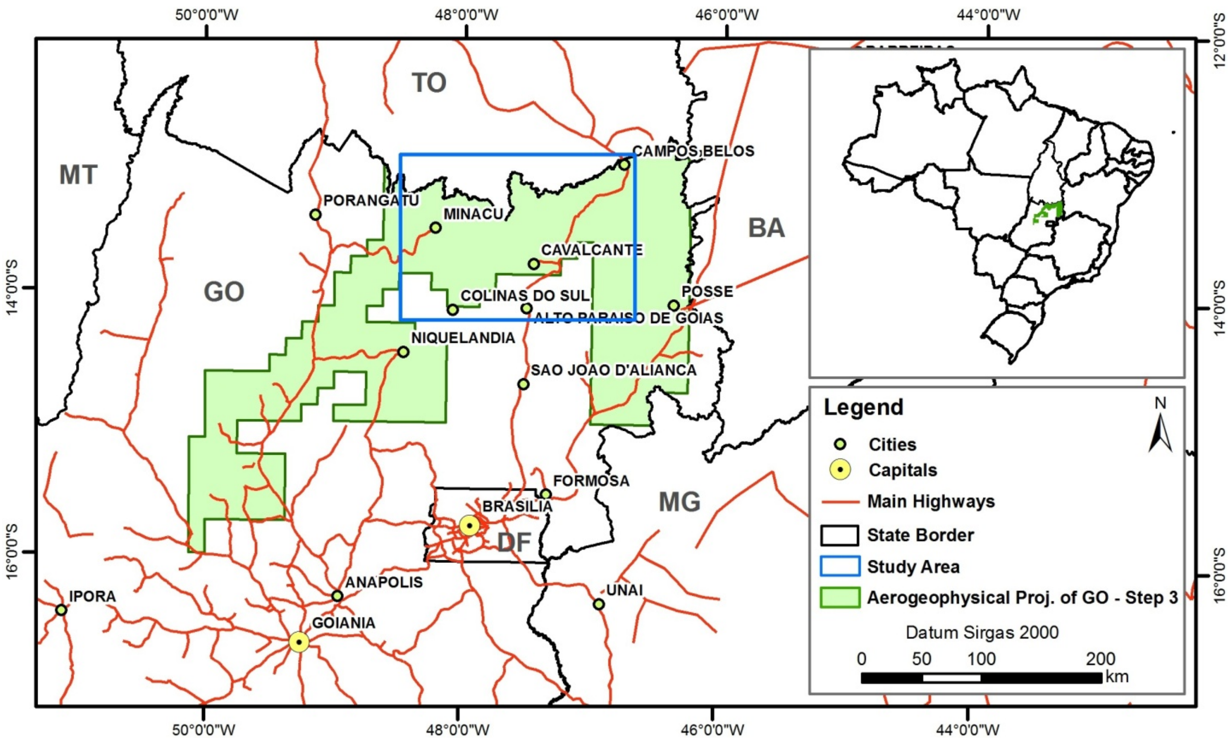

Figure 1 – Map of the study area and the airborne survey used.

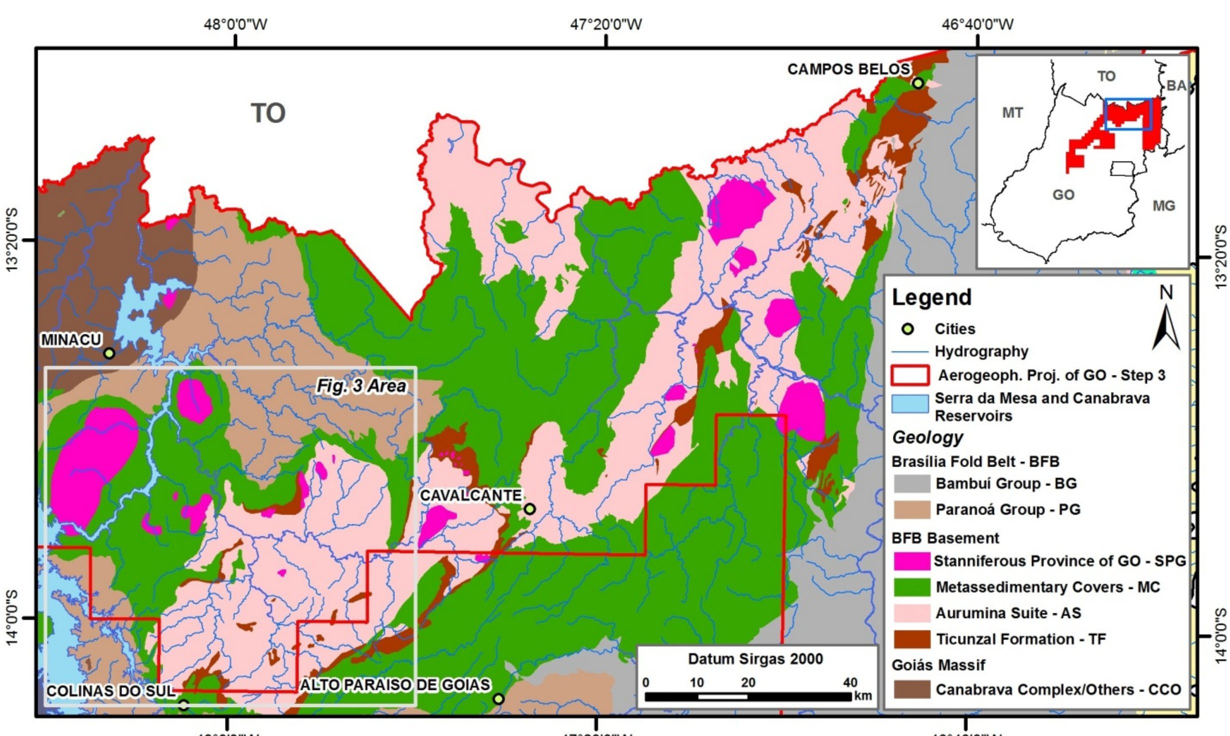

Figure 2 – Simplified geological map of the study area. The Metasedimentary Covers class (MC) encompasses Araí and Serra da Mesa Groups, and the class Canabrava Complex and Others (CCO) encompasses beyond this, the Rio Maranhão Complex and the Palmeirópolis Meta-volcano-sedimentary Sequence.

times higher. Sedimentary rocks exhibit large average uranium concentration variability depending on the various possibilities of source rocks, environments and transport processes. They tend to be depleted in uranium, and can present background similar to granite (Wilford, 2011). Consequently, the element uranium is present in various lithologies and its concentration varies widely, usually depends on the silica content of the rock, and is influenced by geological processes.

Prospecting for uranium is based on the radioactive properties of the element and the pervasive nature of gamma radiation originating from uranium minerals. This radiation is less attenuated by matter than other forms of radioactivity, which means high penetration. Attenuation depends crucially on the medium density since gamma radiation can penetrate several hundred meters of air, though no more than 1 meter of rock or soil (Minty, 1997; Wilford, 2011).

Airborne gamma spectrometry data were originally used in uranium exploration but, in recent decades, started being used on several other applications, such as geological mapping, direct detection of mineral deposits, environmental radioactivity monitoring, estimation of water resources as snow, soil mapping and study of landscape formation processes (Wilford & Minty, 2007). The method is based on the finding that almost all of the gamma radiation detected on Earth's surface comes from the radioactive decay of just three elements: K, U and Th. Element K is detected by gamma radiation emitted by the decay of isotope ^{40}K to ^{40}Ar, while U and Th elements are detected through radiation emitted by the decay of their daughter isotopes, ^{214}Bi and ^{208}Tl, respectively. Since imbalances in the U and Th decay series may occur, the convention is to use the eU and eTh notation, indicating that the inferred concentrations are equivalent to series in equilibrium, which does not always occur, especially for U (Minty, 1997).

Gamma radiation emitted by radionuclides U, Th and K is detected and quantified by sensors installed on aircrafts which are flying low, usually no more than one or two hundred meters. Detectable gamma rays come from the radionuclides present in the 40 cm upper layer of soil or rock (Wilford, 2011). The concentration of K, U and Th in the area covered can be inferred by measuring the number of gamma rays detected per unit time and energy band for each ray. Thus, airborne gamma spectrometry is being used in uranium prospecting, particularly in areas that are vast, of great geodiversity, or inaccessible by land, allowing the collection of data to estimate U concentration in outcropping rocks and soils. However, in areas of great lithological diversity, establishing a uranium concentration to delineate geophysical anomalies becomes a difficult task, since anomalous levels for one lithology often represent background levels for other lithologies.

MATERIALS

We used magnetometry and gamma spectrometry data from the Aerogeophysical Project of Goiás State – Step 3 (Fig. 1), called Paleo-Neoproterozoic of Goiás (also known as Area V), which resulted from an agreement between the Federal Government, through the Geological Survey of Brazil (CPRM) and the Ministry of Mines and Energy; and the Government of Goiás State, through the Department of Industry and Trade and the Funmineral.

The survey was conducted by Lasa Engenharia e Prospecções S.A. in 2006, with 0.5 km spacing between the north-south flight lines, and 5.0 km between the east-west control lines, with a nominal flying height of 100 meters. According to the Technical Report of the project (Lasa, 2006), the data were collected using two aircrafts, a Cessna 404 Titan (PT-FZN), which flew over the Western portion between May 1st and July 10th, 2006, and a Piper Navajo PA31 (PT-WOT), which flew over the eastern portion between June 8th and September 1st, 2006. The data used in this study were obtained exclusively by the aircraft PT-WOT, using an Exploranium GR-820 gamma ray spectrometer, with 256 channels, and sodium iodide crystal detectors activated with thallium, a total volume of 2,560 cubic inches, of which 512 are upward looking and the remaining downward looking crystals.

The aerial magnetometer used was a Scintrex CS-2 with cesium vapor sensor mounted in the tail of the aircraft (Stinger mount), with 20,000 - 95,000 nT sensitivity range and 0.001 nT resolution. The terrestrial magnetometer Overhauser GEM GSM-19 was also used to monitor the diurnal variation of the geomagnetic field. Readings with the gamma ray spectrometer were taken every 1.0 s, and with the magnetometer every 0.1 s, corresponding to a measurement every 80 and 8 meters, respectively, given the approximate flight speed of the aircraft PT-WOT (287 km/h). The gamma ray spectrometry and magnetometry data of the Aerogeophysical Project of Goiás State – Step 3 were corrected and preprocessed to be used in the final processing and interpretation, as detailed in the corresponding Technical Report (Lasa, 2006).

METHODOLOGY

The proposed methodology consists of applying the multiple linear regression technique to the data of the Aerogeophysical Project of Goiás State – Step 3, which covered the areas prospected by Nuclebrás and CNEN in the late 1970s and early 1980s in the northeast of the State. This study aims to highlight the anomalous U concentrations present in the various rock types following the methodology proposed by Pires et al. (2010), which is based on the correlation between environmental concentrations of the radioelements K, U and Th, and also the variation of these concentrations in the different rock types.

According to Pires (1995), Th is considered a good lithological mapper due to its low mobility in the surface environment. Element K, although with higher mobility under the same conditions, is an important element constituent of rock-forming minerals and, thus, indicates the variation of surface lithologies (IAEA, 2003). Thus, the surface concentrations of Th and K can be used to predict the lithology contribution of U, which shows a correlation with the other radioelements. Additionally, Pires et al. (2010) used the magnetometric product of analytic signal amplitude (ASA) as an independent variable to characterize the surface distribution of rock types, based on the principle that at low and middle latitudes this product conforms to the limits of magnetic units, emphasizing that these units are not always outcropping. Thus, Pires et al. (2010) used Eq. (1) to linearly relate these independent variables to uranium levels that should reflect the intrinsic fluctuation of lithology variation:

$$U_{(K,\,Th,\,ASA)} = cte + aK + bTh + cASA \qquad (1)$$

where:

$U_{(K,\,Th,\,ASA)}$ = theoretical U concentration in relation to potassium and thorium concentrations and the analytical signal amplitude;
cte = constant; and
a, b and c = linear regression coefficients for K, Th and ASA, respectively.

The linear regression coefficients were determined from Eq. (1) using the channels of the three radioelements and ASA observed. The present study used the same variables as Pires et al. (2010), but without previous normalization, using separate algorithms for calculating the coefficients, which allows considering the value of the constant zero. Then, the coefficients were used to calculate a theoretical concentration of the element uranium (theoretical U – notation $U_{(K,\,Th,\,ASA)}$) that, for this model should represent the variation of the U concentration in different rocks. Finally, $U_{(K,\,Th,\,ASA)}$ is subtracted from the observed U channel, generating a new uranium concentration, theoretically with a significant attenuation influence from the lithology (anomalous U).

The corresponding uranium prospecting area of the Rio Preto Project was cropped from the original survey and gamma ray spectrometric and magnetic data were used in the multiple regression model. The theoretical U for the entire study area was calculated from the coefficients determined for this area.

Gamma ray spectrometry data preparation

The original radiometric data are arranged in a grid of approximately 80×500 meters and, according to Andrade et al. (1985), uranium mineralizations of the Rio Preto Project are distributed in small elongated bodies following the metamorphic foliation, whose mineralized veins have widths smaller than a meter, i.e., reduced dimensions geometry. Thus, in order to preserve as much as possible the target detection capacity from the original data, taking into account that one or two anomalous points may represent a mineralized body, no spikes correction, no negative values correction, and no normalization for the crustal average was executed, nor were the data interpolated or micro leveled at this multiple regression preparation step, which basically consisted of analyzing the data in table and profile formats.

The usual corrections were applied to a duplicate dataset for comparison. For the duplicate dataset, the eU, eTh and K channel maps were generated using the Bi-directional line gridding – BiGrid interpolator, disregarding the control lines and with 125 m cell (Figs. 3a, 3b and 3c). All processing was performed in the Geosoft Oasis montaj 7.0.1 software.

Magnetic data preparation

The magnetic data are spaced 8 meters, which is 10 times smaller than the gamma ray spectrometry data. For the regression procedure resampling was done for 80 meters, using only the data spatially coinciding spatially with the gamma spectrometry data. The map of the Anomalous Magnetic Field (AMF) was generated from the Total Magnetic Field (TMF) data by subtracting the IGRF. Then, a regular grid with 80 meters cell was generated using the BiGrid interpolator. Before calculating the Analytical Signal Amplitude (ASA), micro leveling was also applied, using the high-pass directional Cosine filter. ASA data (Fig. 3d) coincident with the sample spacing of gamma ray spectrometry data were exported to a table to integrate the regression independent variables.

Data multiple linear regression

According to Pires et al. (2010), multiple linear regression among the estimated radionuclide concentrations can be used to model and remove the effects of geological processes within different rock types. The method is useful in removing gross systematic changes in these concentrations, and can also be used to highlight discrepancies in the average levels distribution within a unit (Pires, 1995). The procedure consists of generating a linear regression model with multiple independent variables and only one dependent variable. Theoretically, the generated model

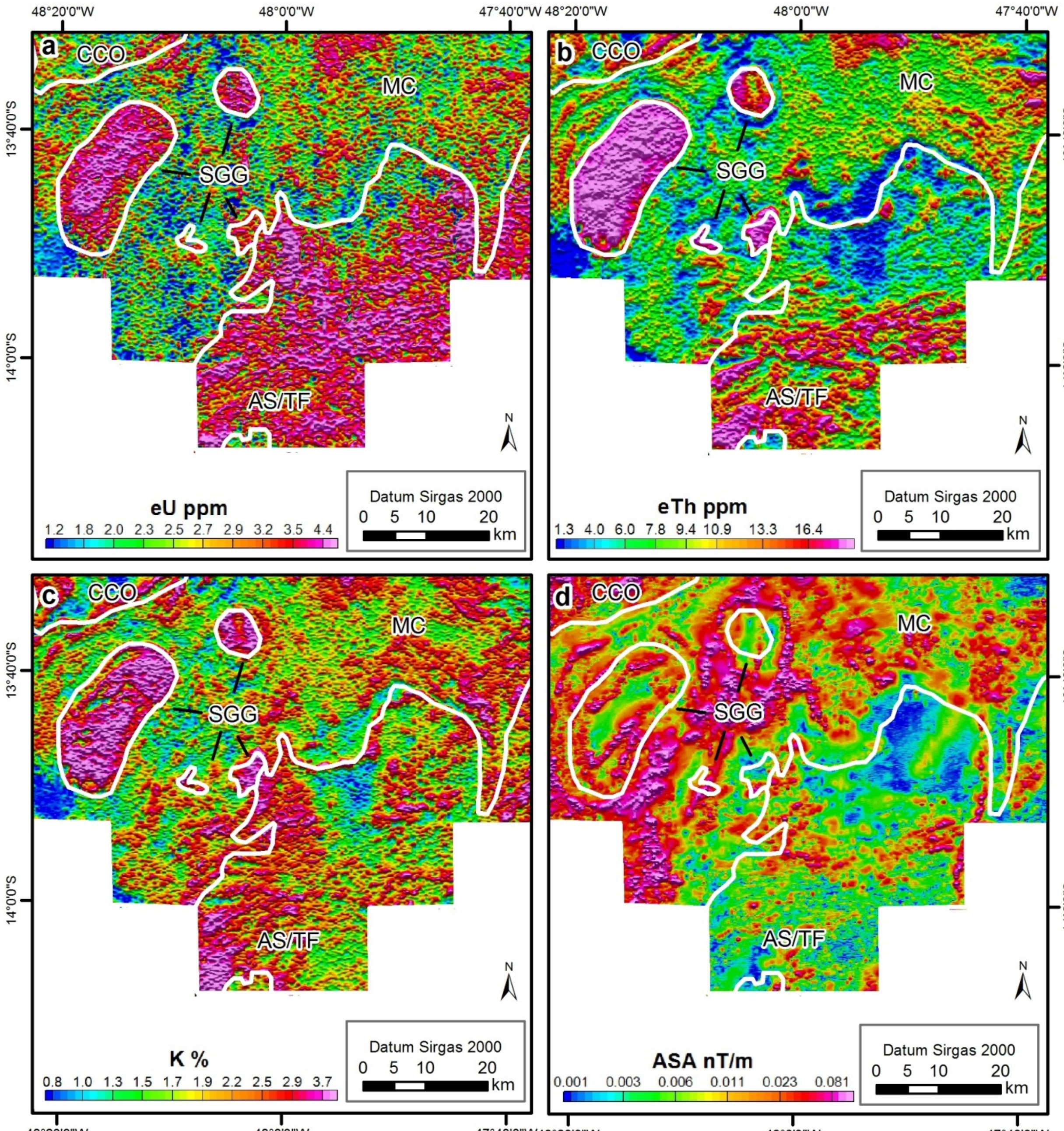

Figure 3 – Maps of airborne geophysical products used in the linear regression model. a – eU map; b – eTh map; c – K map; d – ASA map; AS/TF = Aurumina Suite/Ticunzal Formation; MC = Metasedimentary Covers; SGG = Stanniferous Granites of Goiás; CCO = Canabrava Complex and Others.

allows inferring the contribution of each independent variable in the contents of the dependent variable.

As previously mentioned, the multiple regression model used in this work was obtained from airborne geophysical data restricted to the Rio Preto Project area (Fig. 3). To determine the linear coefficients a, b, and c, the eU, eTh, K, and ASA data were related according to Eq. (1) using the Microsoft Excel Solver software. For the model to be efficient in predicting the lithological contribution in uranium concentrations [U(K, Th, ASA)], there must be a significant correlation between the dependent variable (eU) and each of the independent variables (eTh, K and ASA).

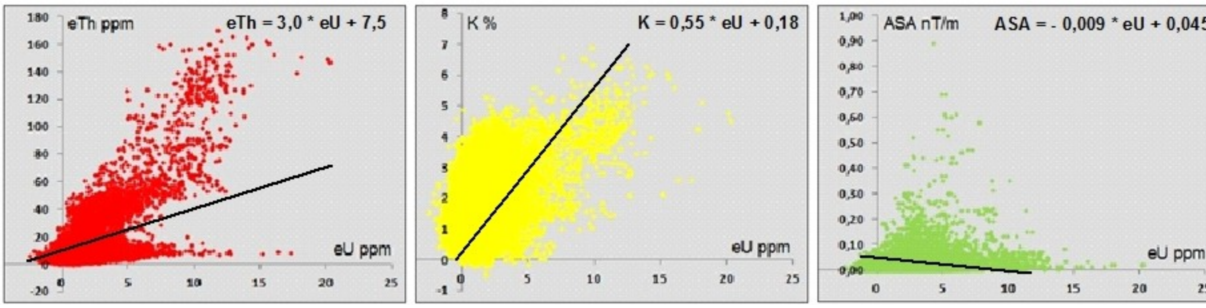

Figure 4 – Scatter plots of the independent variables (eTh, K and ASA) as a function of the dependent variable (eU).

Figure 4 presents the scatter plots of these variables, which indicate good eU correlation with the other radiometric variables and little correlation with the magnetic variable ASA. Chart analysis allows us to infer that eTh and K contributions will be greater than the ASA contribution in predicting the dependent variable, the theoretical U, which reflects uranium concentration variations as a function of the various rock types [U(K, Th, ASA)].

The linear coefficients obtained for the multiple linear regression model of airborne geophysical data of the Rio Preto Project were substituted in Eq. (1) and the constant (cte) was set at zero, which led to Eq. (2).

$$U_{(K,\,Th,\,ASA)} = 0.0645\ eTh + 0.4398\ K + 0.4996\ ASA \qquad (2)$$

This equation applied to the observed independent variables enabled to determine the values corresponding to the theoretical U [U(K, Th, ASA)] for the entire study area, the Rio Preto and Campos Belos projects area, as well.

Subsequently, we subtracted the theoretical from the observed U according to Eq. (3), obtaining values of anomalous concentrations of uranium (anomalous U):

$$U_{AN} = U_{OBS} - U_{(K,\,Th,\,ASA)} \qquad (3)$$

where:
U_{AN} = Anomalous Uranium
U_{OBS} = Observed Uranium.

The anomalous U data were calculated for the entire study area and represent anomalous uranium concentrations, attenuated by lithological influences.

Data presentation and interpretation

The anomalous U map was obtained by BiGrid, with 80 m cell for the entire study area and is shown in Figure 5. This map illustrates the spatial distribution of anomalous uranium concentrations attenuated by lithological influences. The simplified geology contours of the region were delineated on this map, so as to allow observation of abnormal variations in the uranium concentrations in relation with the outcropping rock types in the study area.

Additionally, the ArcGIS 9.3 geographic information system was used to analyze obtained data and integrate them with other sets of data. The obtained U_{AN} values were plotted as points, with this software, and interpolated to a regular grid with 80 meter cell. The Inverse Distance Weighting (IDW) interpolator was used, for its simplicity and its feature of preserving the actual values at the sampling points.

The results of this interpolation were classified in terms of standard deviation, generating an information plan which contains only the two upper ranges of U_{AN} concentrations: (i) the intermediate values range, containing concentrations between the mean plus one and mean plus four standard deviations, i.e., between 1.17 and 4.68 ppm, and (ii) the higher values range, encompassing all values of U_{AN} greater than 4.68 ppm. The upper range was considered representative of areas where uranium mineralization occurrence at the surface is more favorable, and was used as a reference for checking field anomalies.

Data interpretation was done through their integration, in a GIS environment, with geological information and spatial data extracted from bibliography related to Rio Preto Project (Figueiredo Filho et al., 1982) and Campos Belos Project (Andrade et al., 1985). Validation of some anomalies in the field followed.

Field validation

The field survey was carried out between July 20th and 25th, 2011. Six of the major anomalies selected for the Rio Preto and Campos Belos projects areas were verified (Figs. 5b and 5c). The radiometric values in these anomalous regions were measured with a portable RSI gamma spectrometer, RS-230 BGO Super-SPEC model, that with an integration time of 120 seconds, provided maximum eU concentrations around 650 ppm for the anomalies in the Campos Belos region and above the detection limit of the

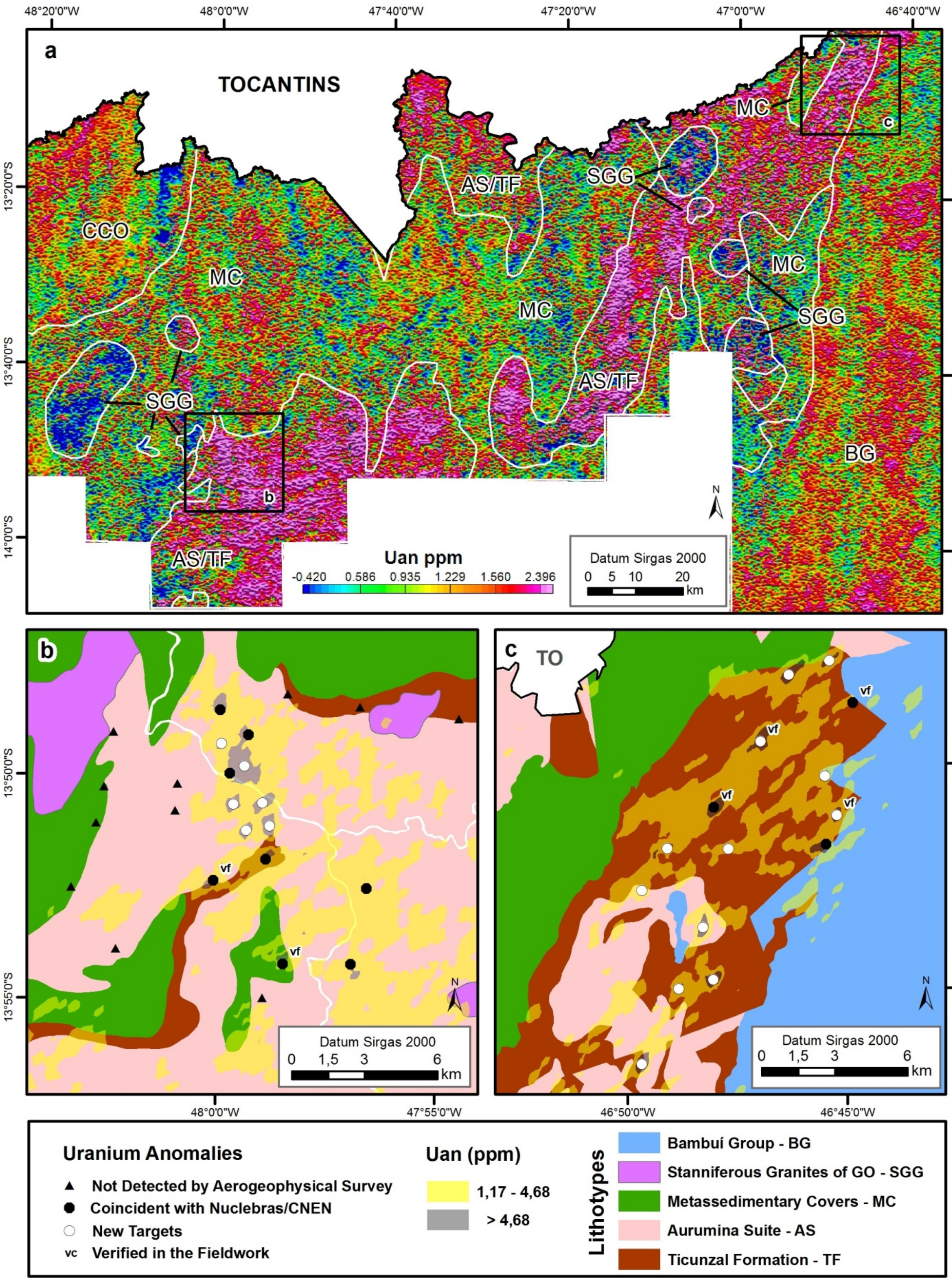

Figure 5 – a) U_{AN} map for the study area, where: AS/TF = Aurumina Suite/Ticunzal Formation; MC = Metasedimentary Covers; SGG = Stanniferous Granites of Goiás; BG = Bambuí Group; CCO = Canabrava Complex and Others. b) and c) are geological maps of the Rio Preto and Campos Belos projects areas, respectively, with anomalous uranium regions and the U anomalies selected.

instrument, greater than 10,000 ppm, on mineralized bodies of Rio Preto region. Traces of old mineral exploration campaigns, like trenches, pits and boreholes made by Nuclebrás and CNEN were also found.

RESULTS AND DISCUSSION

The applied methodology yielded maps of the variables used in the multiple regression (Fig. 3) and the anomalous U map, the final product of the multiple regression model (Fig. 5a). The latter product was also analyzed in GIS, as described in the methodology, to define the regions that are most favorable to the occurrence of uranium mineralization, in the Rio Preto and Campos Belos projects areas (Figs. 5b and 5c, respectively), guiding the fieldwork inspection and enabling its integration with geological data.

The regional simplified geological map (white line) was superimposed to the geophysical products (Figs. 3 and 5a), which allowed to visualize the variation of geophysical signatures according to the different lithologies. For the geological maps of the Rio Preto and Campos Belos projects areas, the anomalous U concentrations bands were superimposed.

The equivalent uranium (eU) map, Figure 3a, has high concentrations in the outcropping region of Aurumina Suite (AS) and Ticunzal Formation (TF) in the southeastern quadrant of the map, as expected. However, high concentrations also occur in the Stanniferous Granites of Goiás (SGG), represented on the map by the Serra da Mesa, Serra Branca, Chapada de São Roque and Florêncio batholiths, from largest to smallest. The metasedimentary covers (MC) have heterogeneous spatial distribution of uranium concentrations, but with much lower average levels when compared to rock types previously described. It is observed that there are some slightly higher concentrations in small confined MC areas.

In the equivalent thorium map (eTh), Figure 3b, high concentrations are once more observed associated with SGG, which allows a clear definition of the contours of these intrusions on the surface. In the southern portion of the AS/TF outcrop area a region of high thorium, possibly associated with some AS intrusions is also observed. The distribution pattern of thorium in MC proves to be very similar to that of uranium, with some highs in the northeastern quadrant of the map.

For the potassium channel (K), Figure 3c, SGG once more show high concentrations, while the patterns for MC and AS/TF appear to be similar. There is a significant region with high potassium in the southwest of AS/TF outcropping area.

The Analytic Signal Amplitude map, Figure 3d, shows little relation with the shapes of outcropping lithologies. It is noteworthy the scarcity of magnetic anomalies in the AS/TF region, which are slightly more frequent in the MC region, especially near SGG intrusions.

Application of the multiple linear regression model generated the U_{AN} map (Fig. 5a), the final product with cells of 80 m. This map shows the spatial distribution of the anomalous U estimated concentrations for the entire study area, which covers the Rio Preto and Campos Belos projects.

The U_{AN} map (Fig. 5a) shows that the rock types associated with SGG have low U concentrations, as opposed to what was found in the equivalent U (eU) map of the Rio Preto Project region (Fig. 3a). Although these granitic bodies demonstrate a pattern opposite to that observed in the uranium channel map, they now represent negative anomalies; most of them still has localized radiometric highs. Probably these residual highs reflect anomalous concentrations within the batholiths or they represent just surface lateritic covers enriched from the weathering processes.

The metasedimentary covers of Serra da Mesa, Araí, and Paranoá Groups still show a heterogeneous pattern in comparison with the eU map, with averages in between the SGG and the AS/TF outcropping regions, plus some randomly distributed local highs.

Map regions related to AS/TF outcrops have the highest average U_{AN} concentrations. The Rio Preto and Campos Belos projects regions were eminent, showing U_{AN} anomalous concentrations above 2 ppm distributed along almost the entire length of these lithologies. Beyond the prospecting regions, a region of strong positive U_{AN} anomalies has been highlighted between the 47°00′W and 47°30′W meridians (Fig. 5a).

The extreme east and northwest of the map of Figure 5a feature lithotypes outside the study area, denominated BG (Bambuí Group) and CCO (Canabrava Complex and others) (Fig. 2). These lithologies are largely covered by soil and show geophysical features similar to MC.

Figures 5b and 5c present geological maps with the main outcropping lithologies of Rio Preto and Campos Belos projects areas, respectively. A reclassification of the U_{AN} map, in which only two classes of anomalous concentrations are represented, is superimposed on the geologic map. The first class includes anomalous U values between the mean plus one and the mean plus four standard deviations (yellow polygon in Figs. 5b and 5c) and the second class corresponds to all bigger values (gray polygon in Figs. 5b and 5c). The points corresponding to the main surface gamma spectrometry anomalies detected by the works of Nuclebrás and CNEN in the 1970s and 1980s (black circles and triangles, Figs. 5b and 5c) are also plotted in these figures. The symbols in Figures 5b and 5c refer to the coincidences of these terrestrial anomalies and the airborne anomalies obtained in this work. The results of processing and fieldwork, presented in these figures, revealed new targets for future research identified by white circles.

The largest anomalous concentrations of the Rio Preto Project area (Fig. 5b) are located in the central region, related to Aurumina Suite and Ticunzal Formation rocks, and coincide with eight terrestrial anomalies previously recorded and six new significant anomalies. Several terrestrial anomalies reported in Nuclebrás documents do not appear in the airborne geophysical data. Such anomalies occur in the peripheral area of the project, near the escarpments of Araí Group rocks, which may explain their non-detection, since the large topographic gradient of these regions forces the aircraft to fly higher.

The largest anomalies of the Campos Belos Project area (Fig. 5c) occur dispersed throughout the northeast direction, confined in the Ticunzal Formation rocks. Three coincidences of the Campos Belos Project terrestrial anomalies with airborne anomalies detected in this work were identified, along with twelve significant anomalies not previously described.

CONCLUSIONS

As shown in Pires et al. (2010), the results presented here also demonstrate the effectiveness of the method in mitigating lithological influences on uranium concentrations obtained by aerial surveys in areas with diversified lithology. The attenuation of U levels observed for the SGG, in the comparison between the eU map (Fig. 3a) and the anomalous uranium map (Fig. 5a), demonstrates the removal of their elevated uranium background.

On the other hand, the U levels in admittedly anomalous lithologies, Aurumina Suite and Ticunzal Formation, were highlighted with the application of multiple linear regression, which also supports the applicability of the technique in highlighting anomalous uranium concentrations within a single lithotype.

Furthermore, the identification of airborne anomalies correlated to terrestrial anomalies of Nuclebrás and CNEN prospecting studies demonstrates the potential of the methodology adopted to identify occurrences of U mineralized bodies in the region.

The results of this study also revealed the existence of significant anomalies in regions outside the areas prospected by the Rio Preto and Campos Belos projects, suggesting that implementation of exploratory research in greater detail in these regions is promising.

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