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Statistical enhancement of airborne gamma-ray uranium anomalies: Minimizing the lithological background contribution in mineral exploration

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ABSTRACT

A methodological proposal is presented for uranium prospection using multiple regression of aerogeophysical data (gamma-spectrometry and magnetometry) via a case study in a large and geologically complex area in central Brazil, where known uranium deposits occur. The model seeks to identify and minimize the background variability in uranium concentration for the different lithotypes present in the study area. The multiple regression model is obtained based on the thorium channel data, the eTh/K, eU/K ratios and the magnetic field analytical signal amplitude. Areas with high uranium concentration, in various lithotypes, are highlighted by the subtraction of the regression model obtained from the uranium values measured during the aerial survey. The study area covers part of the southeastern region of the Goiás state, including the Catalão I Complex, which hosts a phosphate mine and includes well-known uranium anomalies as well as rare earth elements associated with the phosphate deposits. The proposed method reveals the presence of anomalous areas as a function of the independent variables, represented by the geophysical properties and the different lithotypes that constitute the geological environment. Besides areas with high uranium contents associated with the Catalão I Complex, new anomalous areas associated with other types of geological environments could be identified. The targets found by the application of the proposed method, were checked in the field via geochemical analysis of rock samples in addition to in situ measurements with a portable gamma-spectrometer. Field measurements showed that, in all cases analyzed, uranium contents presented values above the average concentration of this radioelement in the earth's crust. Geochemical analyzes results from the collected samples confirmed our results by revealing uranium levels ranging from 3.5 to 15.9 ppm. The presented method was successful in identifying specific sites of high uranium concentration via aerogeophysical data, previously concealed by the geological background.

1. Introduction

Currently, only about 50% of the world's uranium demand is met. Very few countries are exporters or have the capacity to meet their own demand. Brazil owns one of the greatest reserves in the world, although only a small area of its territory has been prospected.

Uranium, a reactive metal, has an average abundance of about 3 ppm in the Earth's crust. The most important uranium minerals are uraninite (pitchblende), uranoesferrite, uranothorite and uranothorianite. Mean values of uranium in crustal rocks vary significantly. The lowest mean concentrations, less than 2 ppm, are found in sedimentary and intrusive mafic rocks (Dickson and Scott, 1997). The highest average concentrations of uranium are associated with intermediate, intrusive or extrusive alkali-feldspathoid rocks, reaching about 56 ppm (Killeen, 1979). Therefore, anomalous concentrations of uranium depend on the type of rock and the processes of mobilization and reconcentration occurring during the geological history.

Aerial gamma-spectrometric surveys are important tools for target selection in uranium exploration (IAEA, 2003). However, the simple field inspection of sites containing high estimated values of uranium concentration may not be an adequate strategy, due to high content variation of this element in different rock types associated with diverse geological environments. The establishment of a content value that may represent an anomalous concentration of uranium depends, among other aspects, on the lithotype. Concentrations of 4 ppm can be considered anomalous in carbonate rocks, whereas in granitic rocks these values need to be at least one order of magnitude higher (IAEA, 2003).

In the present work, we propose the statistical treatment of aerial

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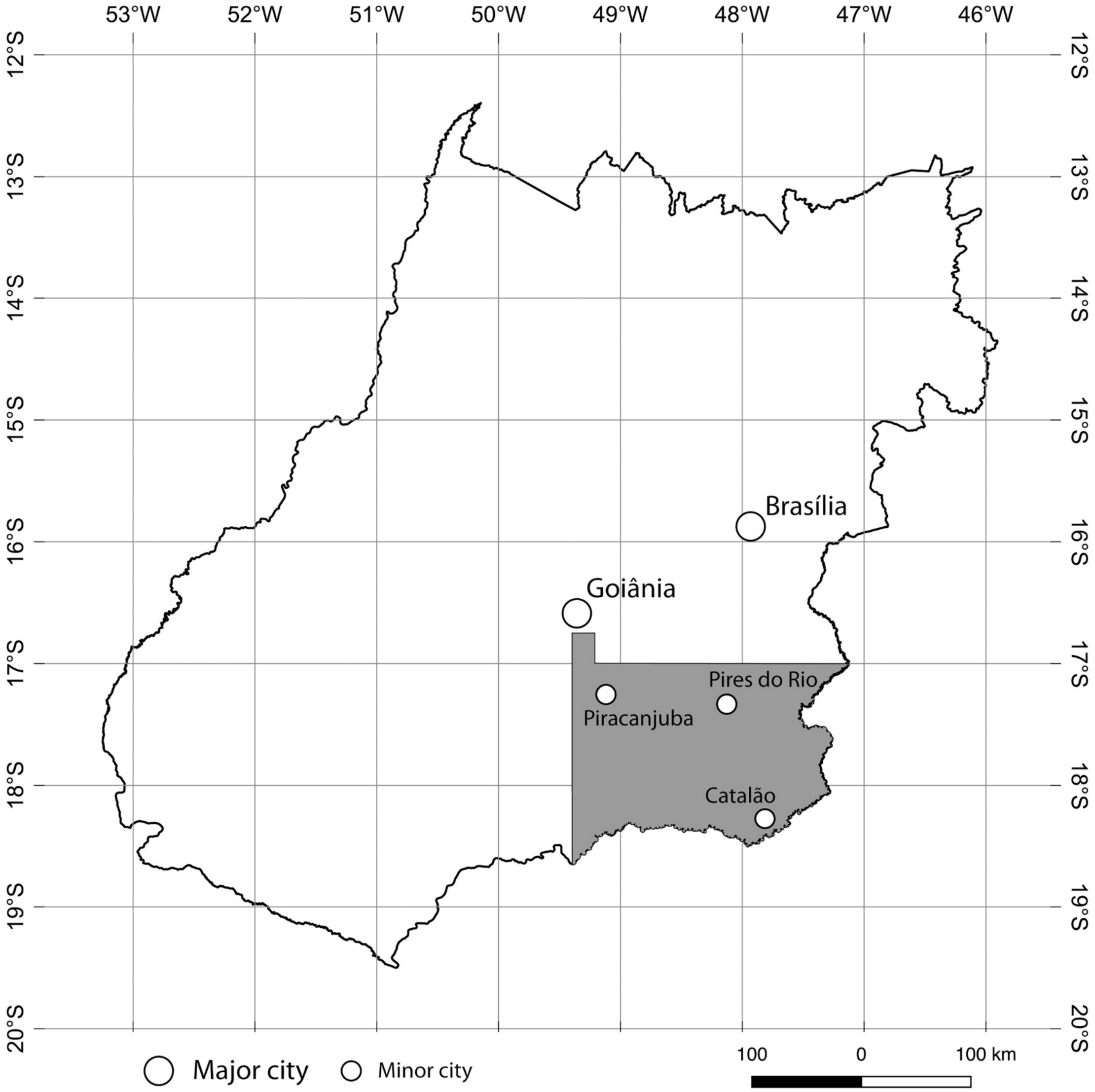

Fig. 1. Location map of the aerial survey area used in this study (in grey) in the Goiás state, Brazil.

gamma-spectrometric data aiming to highlight anomalous concentrations of uranium with respect to the geological environment in which they are located. In this context, we use the data acquired by the Geophysical Aerial Survey of Goiás State, more specifically the Area 4 data, that cover the southeastern region of the state. The survey project was conducted by the government of Goiás State in agreement with the Brazilian Ministry of Geology, Mining and Mineral Transformation, with participation of the Brazilian Geological Service (SGB/CPRM) (Fig. 1).

Simple or Multiple Linear Regression techniques involving estimated concentrations of radioelements can be used to model and remove the effects of geological processes within interpreted units (IAEA, 2003). The regression model is subtracted from the data of each unit and the residues are highlighted. The method may be useful to remove gross systematic changes in the concentration of radioelements or to highlight values that differ from the mean distribution of radioelements contents within the interpreted unit.

The distribution of magnetic intensity also reflects the distribution of lithotypes in the earth's crust. In low and medium latitudes, the analytical signal amplitude can produce satisfactory results for the investigation of the magnetic sources. The analytical signal amplitude is obtained from the magnetic field derivatives in the x, y and z directions. This mathematical tool enhances short wavelength anomalies associated with shallower magnetic sources. The analytical signal amplitude product was used as an additional information source to map the surface distribution of lithotypes of the region.

In the present study, we investigate the statistical dependence of the uranium concentration, estimated from the aerial survey, to the other radioelements and their reasons. The dependence of uranium concentration to the magnetic response of the area is also investigated through the use of the amplitude of the analytical signal.

The multiple regression technique was applied to gamma-spectrometric and analytical signal amplitude data aiming to highlight anomalous concentrations of uranium in different lithotypes.

1.1. *Geological context*

In the geotectonic framework of South America, the study region is located in the Tocantins Structural Province (Almeida et al., 1977, 1981; Almeida and Hasui, 1984). The Brasília Fold Belt (BFB) is the main orogenic unit of the Tocantins Province, generated by the Neoproterozoic Brasiliano orogenesis.

The BFB presents N—S orientation and approximately 1000 km of extension, covering a vast area over three different states in central Brazil. It is marked by two segments of distinct orientation: a northern segment, NE oriented and a southern segment, oriented NW. These two

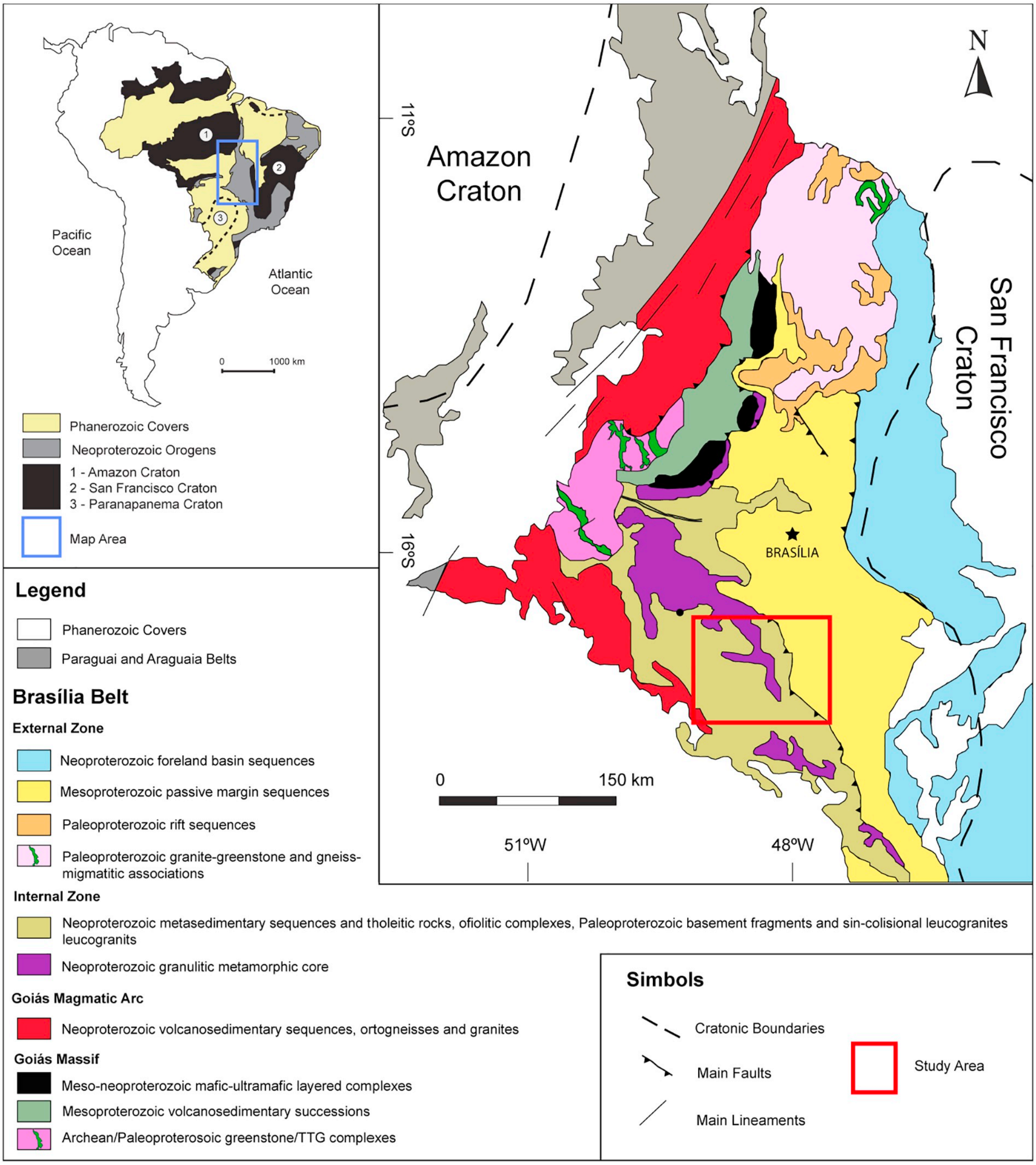

Fig. 2. Simplified map of the Brasília Fold Belt (BFB). (Modified from Fuck et al., 1994).

segments have distinct deformational and metamorphic features, converging at the height of the Brasilia parallel (15°S) and forming the Pyrenees Syntax, an orogenic flexure characterized by EW oriented structures (Valeriano et al., 2004). According to Fuck et al. (1994), the Brasília Fold Belt can also be divided as follows: Internal Zone, External Zone, Goiás Magmatic Arc and Goiás Massif.

The study area is located in the central portion of the southern segment of the Brasília Fold Belt, covering portions of its internal and external zones (Fig. 2). (See Fig. 3.)

The outer zone of the BFB is formed essentially by metasedimentary units with plataformal characteristics (Araí Group, Paleoproterozoic, and Canastra, Paranoá, Vazante, Ibiá and Bambuí Groups, of Neoproterozoic ages), typical of passive margin environments. Paleoproterozoic orthogneissic basement segments are exposed in the north of this zone and in its central sector (Freitas-Silva and Oliveira, 1999), and are interpreted as extension of the São Francisco Craton basement, reworked by the Brasiliano Orogenesis (Fuck et al., 2005). In the northern external zone, magmatism is represented by bimodal volcanism and acid-type plutonism, related to the evolution of the Araí rift. In the central and southern portions, such magmatism is absent or restricted to local intrusions of gabbroic and alkaline bodies.

For all the eastern segment of the external zone, the metamorphism does not exceed the anchimetamorphic grade, reaching low to medium greenschist facies in its western segment. A thin-skinned tectonic deformation, with nappes and inverse fault structures, constitutes the general deformation pattern of the zone (Dardenne, 1978).

The internal zone is composed mainly of metasedimentary rocks of the Araxá Group and the Anápolis-Itaúçu Complex, both of

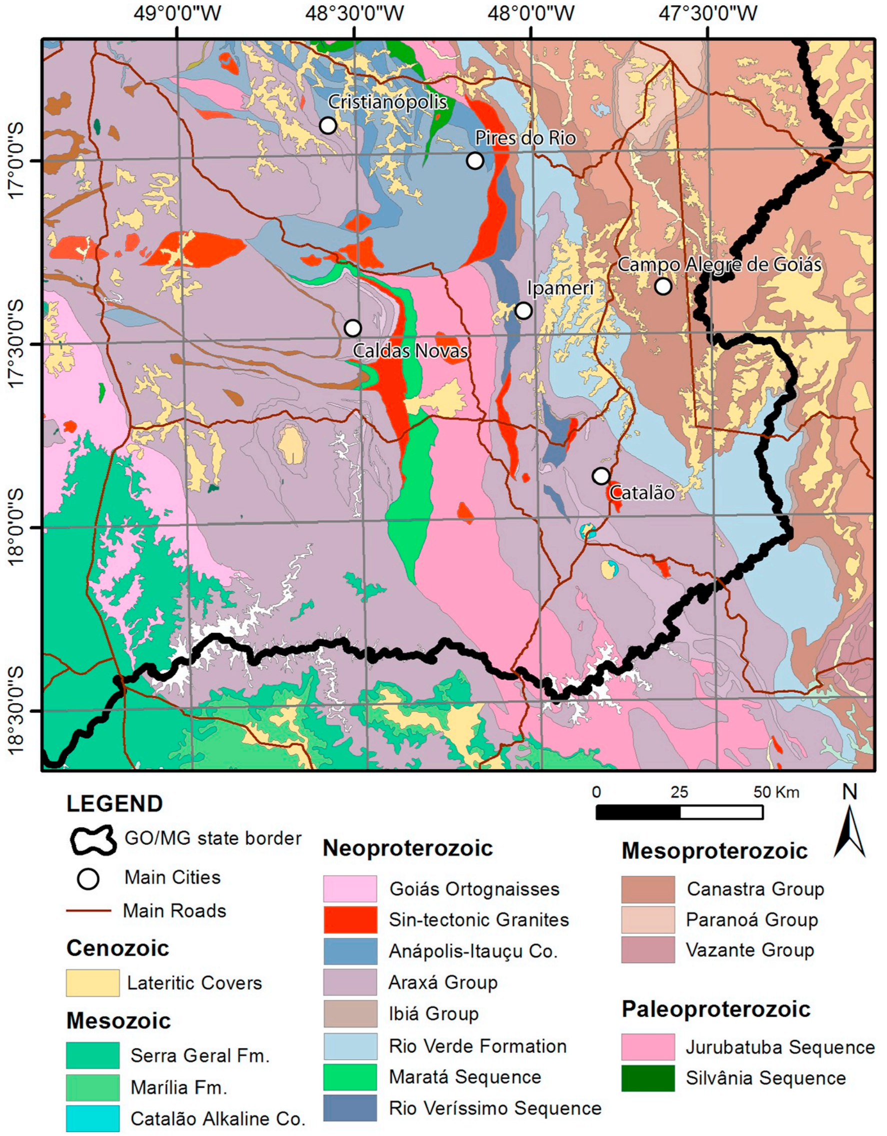

Fig. 3. Geologic map of the study area (after CPRM – Brazilian Geological Service).

Neoproterozoic age. It is bordered to the east by the external zone and to the west by the Goiás Massif, interpreted as a microcontinent composed by Archean and Proterozoic rocks involved in Brazilian orogenic processes. Bordering the Goiás Massif to the west, the Goiás Magmatic Arc is composed of orthogneisses, metavolcanic and metasedimentary rocks of juvenile crust generated in magmatic arc environments from the Neoproterozoic (Pimentel et al., 2000).

The study area includes intrusions of the Alto Paranaíba Igneous Province, of Neocretaceous age. It is one of the many alkaline provinces known in Brazil (Fig. 4). The province consists of a group of kamafugitic affiliation rocks with carbonatic and ultramafic associations. It relates with a topographic and gravimetric high of N55W direction, and is associated with Proterozoic rocks, separating the Paraná and São Francisco basins (Campos and Dardenne, 1997). The alkaline rocks occur in the form of plutonic complexes, dikes, pipes, plugs, diatoms, lava flows and pyroclastic deposits (Gibson et al., 1995; Brod et al., 2004). The province generated important mineral deposits such as the Catalão I and II complexes in southern Goiás state and Serra Negra, Salitre I, II and III, Araxá and Tapira, in western Minas Gerais state (Jácomo, 2010).

1.2. Uranium occurrences in Goiás State

In the 1970s and 1980s, aerogeophysical projects were carried out through a CPRM/DNPM agreement and used by NUCLEBRÁS and CNEN for the purpose of prospecting uranium occurrences in Brazil. In Goiás state, several important anomalies were discovered (Figueiredo and Oesterlen, 1981).

According to Lacerda Filho et al. (1999), the main types of uranium deposits are those associated with: Cenozoic and Mesozoic sandstones; Paleozoic to Archean/Proterozoic quartz veins and pegmatites (sulfide or not); Proterozoic to Archean unconformity-related; and Proterozoic to Archean conglomerates. It is observed that 72% of all types of uranium deposits occur in association with these four environments, and 42% of the deposits are distributed in sandstones of non-folded sedimentary sequences.

Five uranium deposits are known in the Goiás state belonging to two types of environments. Only one of them is associated with the Ponta Grossa Formation feldspatic sandstones, Paraná Basin, located in the municipality of Amorinópolis, with a total reserve of 5000 metric tons of U_3O_8. The others are associated with intrusive granites from the Aurumina suite in the metasedimentary Ticunzal Formation, and are related to metasomatic processes (albithites), with 1000 tons of ore in

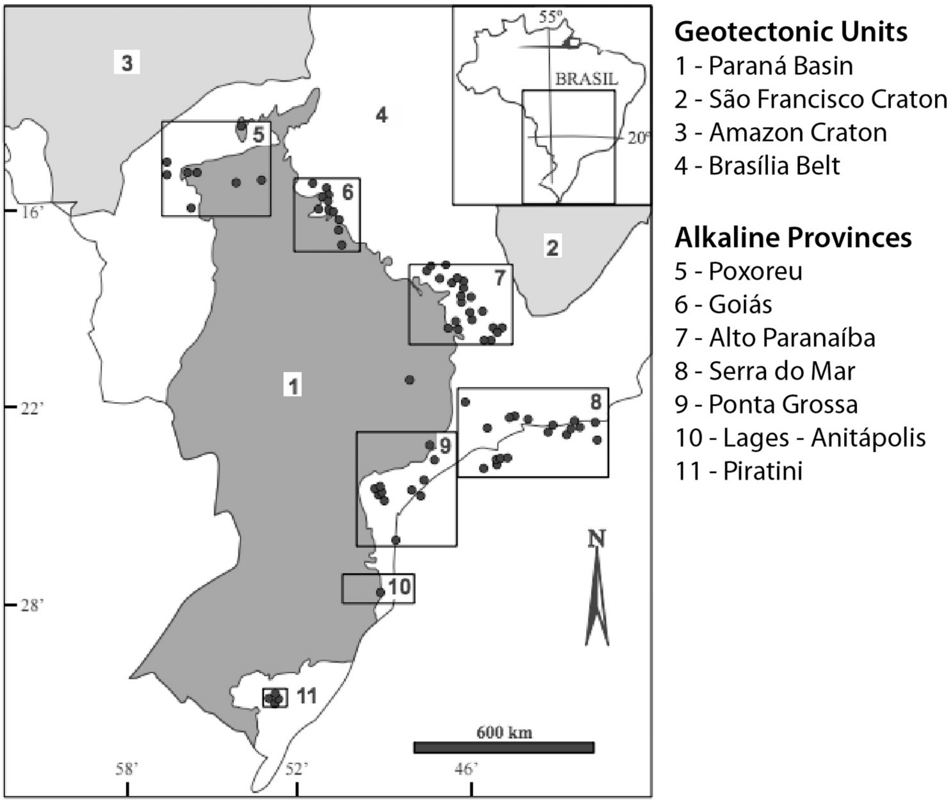

Fig. 4. Alkaline provinces of the central-southern region in Brazil (Navarro et al., 2014).

Table 1
Area 4 aerogeophysical survey technical characteristics.

Project	Area 4
CPRM code	3009
Coordinates	-52,50° a -48,25° e -14,625° a -17,75°
Datum	SAD 69
Methods	Magnetometry and Gamma-spectrometry
Contractor	Governo do Estado de Goiás/SIC-MME/CPRM
Hired company	LASA Engenharia e Prospecções S.A.
Period	03/07 a 24/11/2004
Profile total length	135.756,53 km
Sampling interval	0,1 s (magnetometry) e 1,0 s (gamma-spectrometry)
Flight height	100 m
Total area	58.834 km^2
Flight line direction	N-S
Flight line spacing	0,5 km
Control line direction	E–W
Control line spacing	5 km
Gamma time integration	1 s

the municipalities of Campos Belos and Cavalcante (Rio Preto). These deposits were prospected by NUCLEBRÁS (Pires, 2013). There are, however, some metallotects with a significant potential for the formation of uranium deposits, such as the orthomagmatic deposits, associated with alkaligranites, syenites and carbonatites.

In Goiás state there are favorable prospects for uranium deposits associated with the 134 Alkali Province in the south and the abovementioned Alto Paranaíba Magmatic Province, as well as deposits associated with albitization processes, such as the uranium deposit occurring in the north of the state, near Campos Belos municipality, an uraninite deposit associated with albithites in a shear zone, studied by NUCLAM (Lacerda Filho et al., 1999).

1.3. Aerogeophysical data

The study area is part of the "Goiás State Aerogeophysical Survey Project", conducted by the State of Goiás in agreement with the Secretary of Geology, Mining and Mineral Transformation of the MME (Ministry of Mines and Energy), with participation of the Brazilian Geological Survey, known by the acronym CPRM.

The main objective of the project was to assist the mining and mineral resources sector with the acquisition and the interpretation of airborne and gamma ray spectrometer survey in the Goiás area. The survey results are used for the identification of anomalous geophysical targets that may represent new potential target areas for mineral research.

During these aerial surveys, approximately 60,000 km^2 of the southwest region of Goiás was covered by the project denominated Area 4 – Southern Brasília Belt (Fig. 1). A summary of the airborne survey parameters is presented in Table 1.

1.4. Data acquisition and processing

The acquisition of the magnetic data was done using the Scintrex CS-2 magnetometer with stinger mounted sensor. The signal is sent to the aeromagnetic capture and compensation system and presented a resolution of 0.001 nT and recording range of 20,000 to 950,000 nT. As the magnetometer readings were made every 0.05 s, it equates to an average of 280 km/h of the aircraft, approximately 3.9 m in the ground.

For the evaluation of the magnetic quality of the aircraft system, complete tests were performed. The performance of the aeromagnetic system, term after these tests, did not exceed 2 nT, after a correction of the diurnal evolution. For gamma-ray spectrometry, the spectrophotometer EXPLORANIUM, model GR-820, of 256 spectral channels was used. The spectrum of each detector is analyzed for the determination of potassium, uranium and thorium photo peaks. A linear correction was applied individually to each crystal, keeping the spectrum

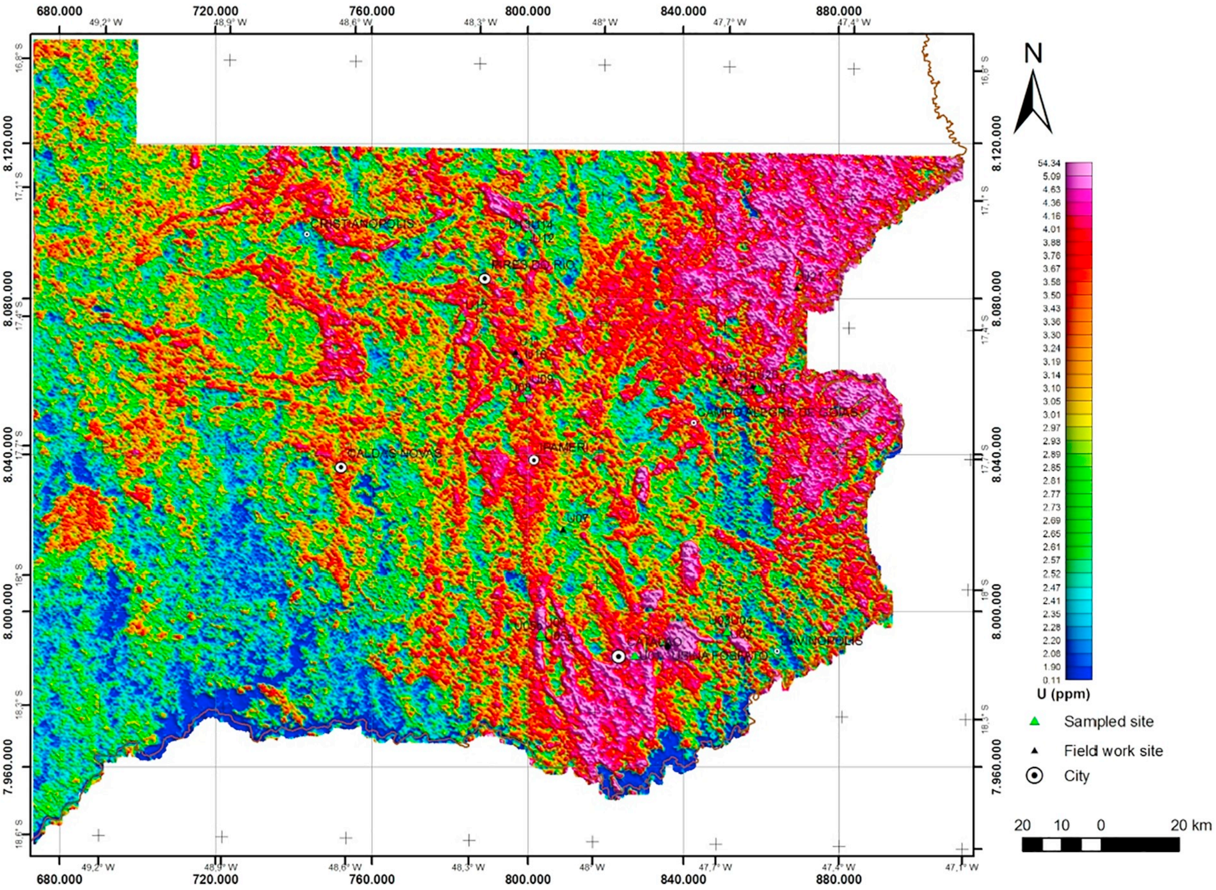

Fig. 5. Equivalent uranium map (eU) in ppm.

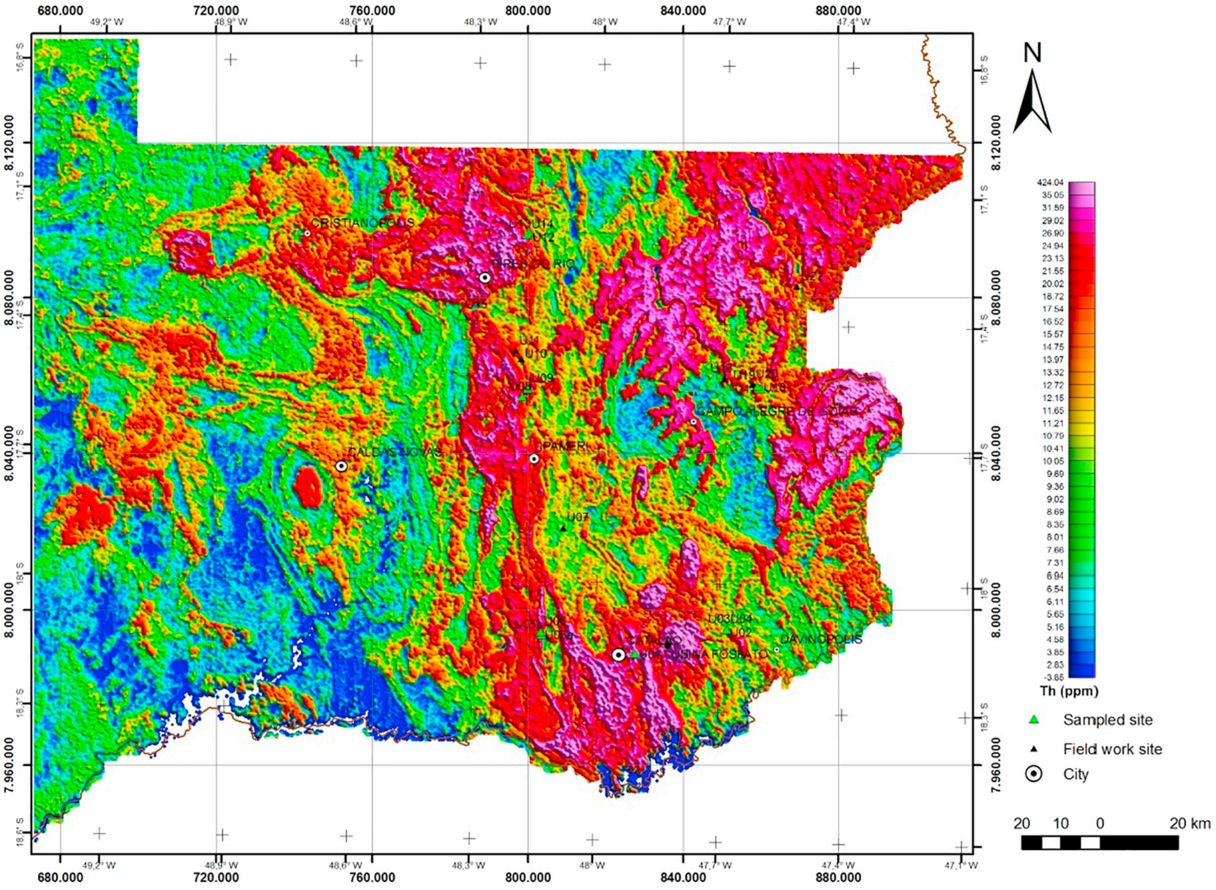

Fig. 6. Equivalent thorium map (eTh) in ppm.

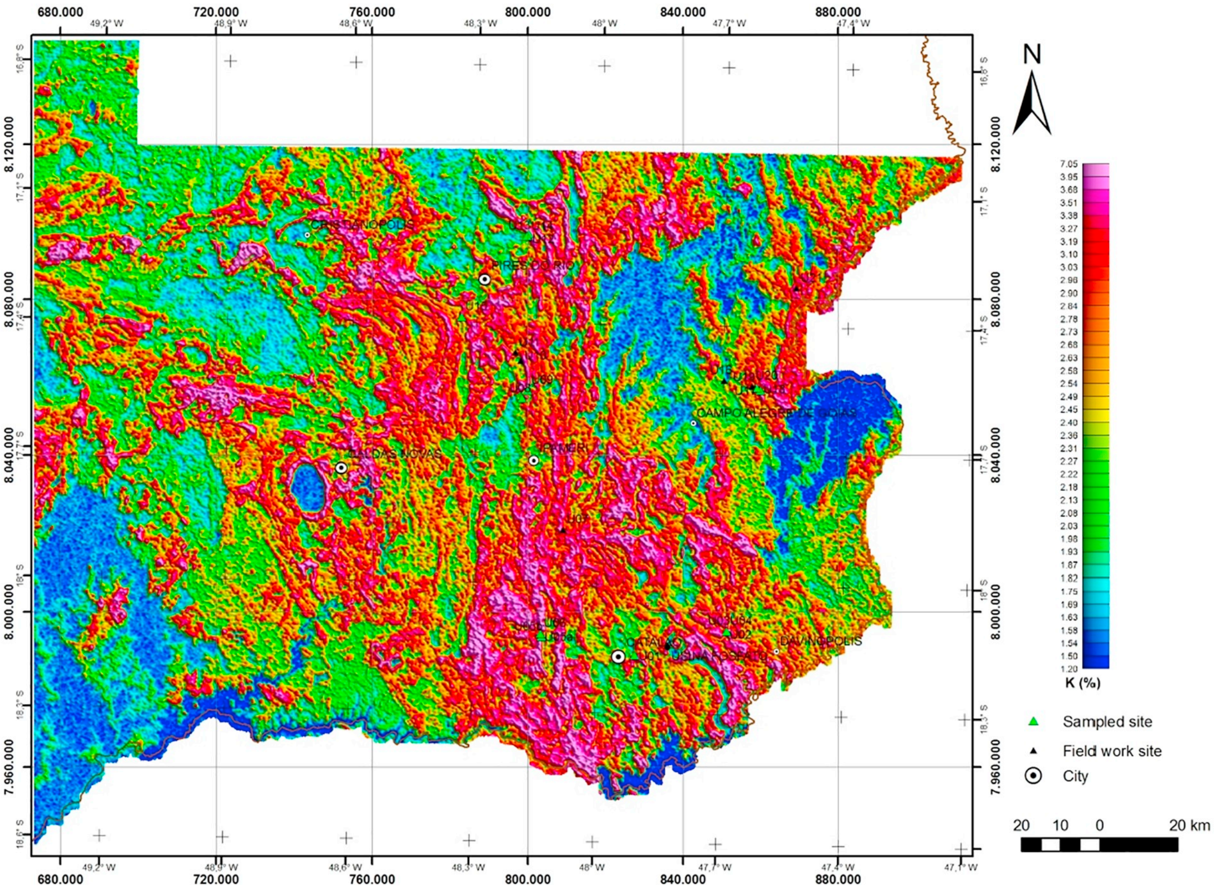

Fig. 7. Potassium map (K) in percentage (%).

permanently aligned. The detected gamma radiations were summed and the readings reduced to a single output of 256 spectral channels. The correspondence between the spectrometer series and the energy bands was as follows:

- Total Count: from 0.41 to 2.81 MeV corresponding to channels from 34 to 233;
- Potassium: 1.37 to 1.57 MeV, corresponding to channels 115 to 131;
- Uranium: from 1.66 to 1.86 MeV, corresponding to channels from 139 to 155; and
- Thorium: from 2.41 to 2.81 MeV, corresponding to channels 202 to 233.

The readings were made at 1 s intervals, implying in a sample spacing, along a profile of 78 m. The entire gamma-spectrometric system was calibrated following the standards by the International Atomic Energy Agency (IAEA, 2003).

The software Oasis Montaj version 7.1 of the Geosoft system, was used for processing the data, in addition to other pre-processing routines, which allowed the export of in-flight binary data to the XYZ GEOSOFT ASCII format. The raw data recorded in binary format were converted directly to databases in the GDB format, where the corrected positioning information and all other channels recorded in the aircraft were grouped together.

The coordinates registered in the aircraft were converted from the WGS-84 system to the Córrego Alegre Datum. The UTM coordinates were referenced to the central meridian 45°W (zone UTM 23S).

1.5. Magnetometry data processing

The processing of the raw data of the Cesium magnetometer by the aircraft acquisition system introduces a time delay in the compensated magnetometric data, as well as the position of the GPS receiving antenna, relative to the position of the magnetometric sensor. This causes a mismatch between the positioning value (X and Y) and the value of the field being sampled in the same time interval. Thus, a correction called Parallax Correction or Lag Correction was applied based on flight line data for calibration.

The values obtained by a base magnetometer were initially subtracted from the magnetic field readings carried out on board the aircraft, with the sampling time as the common variable, with a fixed precision of tenths of a second. The resulting values provided the total intensity of the magnetic field with corrected diurnal variation.

The leveling of the profiles was done using Oasis Montaj software version 7.1 of the Geosoft system. This process basically consists of adjusting the control lines based on the average of the differences (or 1st order difference) with the flight lines. This procedure assumes that such differences are randomly distributed, so that a trend of at most 1st order defines the difference between the flight and control lines.

The survey data were further microlevelled to eliminate any "slope" residue remained. The process involved the generation of two auxiliary grids resulting from the application of Butterworth high pass filters (wave length of about 4 times the flight line spacing) and directional cosine acting in the direction of the flight lines and perpendicularly to them, followed by the creation of a final decorrugated grid. The latter, subtracted from a normal grid will, in turn, express the leveling error to be subtracted from the data pre-graded according to the initial procedure described above.

The removal of the International Geomagnetic Reference Field (IGRF) obeyed the routine included in the Oasis Montaj System, which basically consists of the definition of the trend surface that expresses the behavior of the international geomagnetic field in the project area.

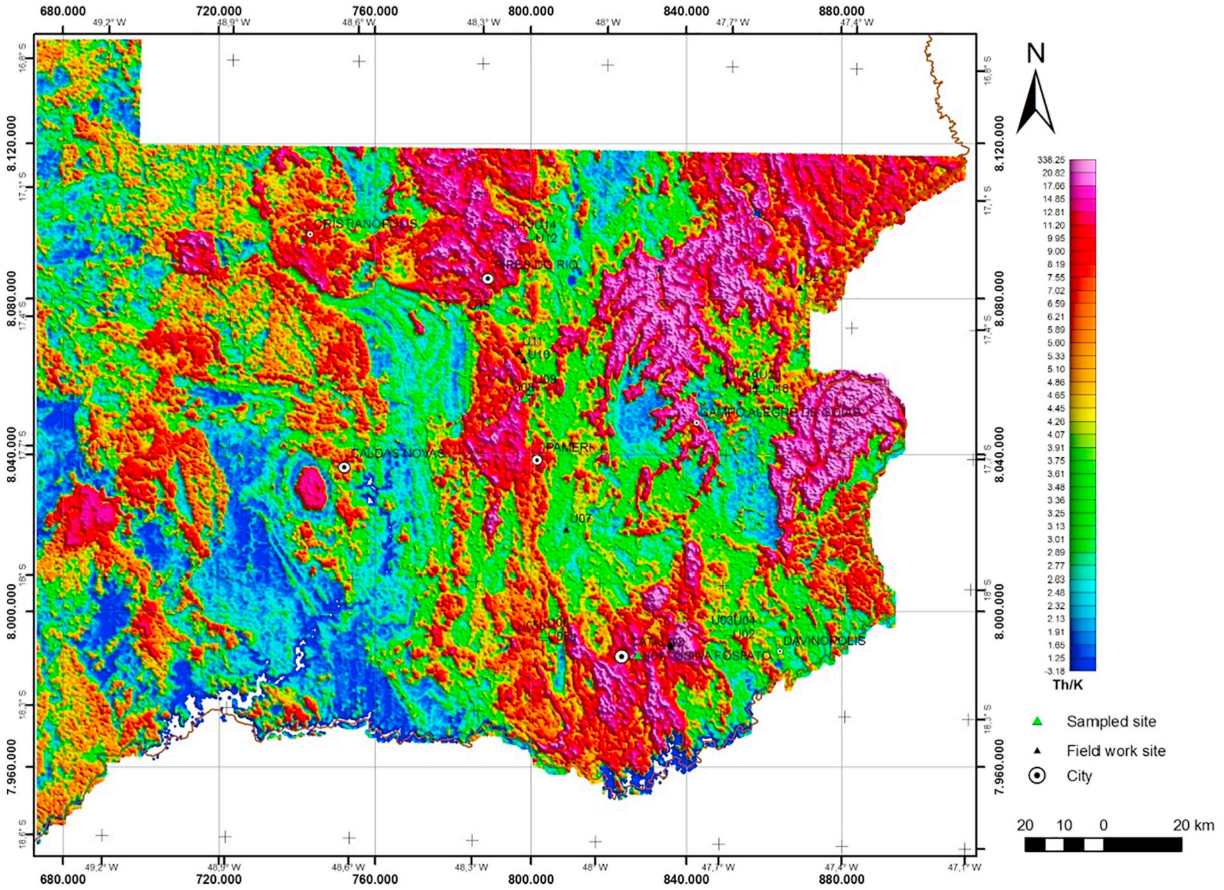

Fig. 8. eTh/K ratio map.

This area was defined based on the value of the IGRF, considering the altitude of 1000 m, referring to the time of the aerial survey. The corrected total magnetic field for each of the sampled points was obtained by subtracting the calculated IGRF value from the total microlevelled field. The resulting values are the anomalous field values reduced total magnetic field of the IGRF).

1.6. Gamma-ray spectrometry data processing

The processing of gamma-spectrometric data followed the procedures recommended in Section 4, Serial Number 323, of the International Atomic Energy Agency Technical Report, entitled “Airborne gamma ray spectrometer surveying”. The routine contained in Geosoft's Oasis-RPS, radiometric processing system was used.

The “dead time” correction consisted in dividing the counts of the radiometric channels by the value of the live time recorded by the apparatus, thus normalizing the raw values of the total count channels, potassium, uranium, thorium and uranium upward for counts per second. The flight height was adjusted based on the ambient temperature and pressure using the formula (IAEA, 2003):

$$\mathbf{he} = \mathbf{h}\,(273.15/\mathbf{T} + 273.15) \times (\mathbf{P}/1013.25) \quad (1)$$

where: **h** - flight height measured by radar altimeter in meters, **T** - air temperature measured in °C, **P** - atmospheric pressure in millibar.

The atmospheric pressure was obtained from the altitude measured by the barometric altimeter of the aircraft. The background was obtained through the sum of the contributions of the background of the aircraft and the cosmic radiation in each of the gamma-spectrometer windows. The calculation of aircraft contributions and cosmic radiation was conducted using the formula (IAEA, 1991):

$$\mathbf{N} = \mathbf{a} + \mathbf{bC} \quad (2)$$

where: **N** - sum of the two contributions (in cps), **a** - background of the aircraft in each window of the range spectrometer, **C** - cosmic radiation channel, **b** - ratio between the count in a certain window and the count in the cosmic channel.

The coefficients applied to the data (Airplane Background and Cosmic Stripping Ratios) were defined by the cosmic flight over the sea, in an area far from the coast. The effect of the radon background, in turn, was determined from the measurements made in the uranium window by the upward looking detector.

The correction of the Compton Effect was applied with the main objective of eliminating the influence of the radiation attributed to the higher energy channels that penetrate the low energy channels, namely: thorium contributions in uranium and potassium, as well as the contribution of uranium in the potassium channel. The aim of the altimetry correction was to refer the radiometric values to the nominal height of the aerial survey (100 m), eliminating false anomalies caused by elevations in the terrain. This procedure followed the indications issued by the IAEA (IAEA, 1991).

Finally, the sensitivities of the aircraft detectors for the potassium, uranium and thorium windows were determined on the basis of the ratios between measurements on board (N) and on land (C), with the application of the expression:

$$\mathbf{S} = \mathbf{N}/\mathbf{C} \quad (3)$$

where: **S** corresponds to the sensitivity for each window, **N** is the average of the corrected counts (in cps) for each channel referring to the height of the survey (100 m) and located in the stretch of interest of the ground stations used, **C** is the mean of the concentrations for each channel of the land stations of interest.

To calculate the Exposure Rate of the total counting channel (in μR/h), the formula provided by the IAEA (IAEA, 1991) was used:

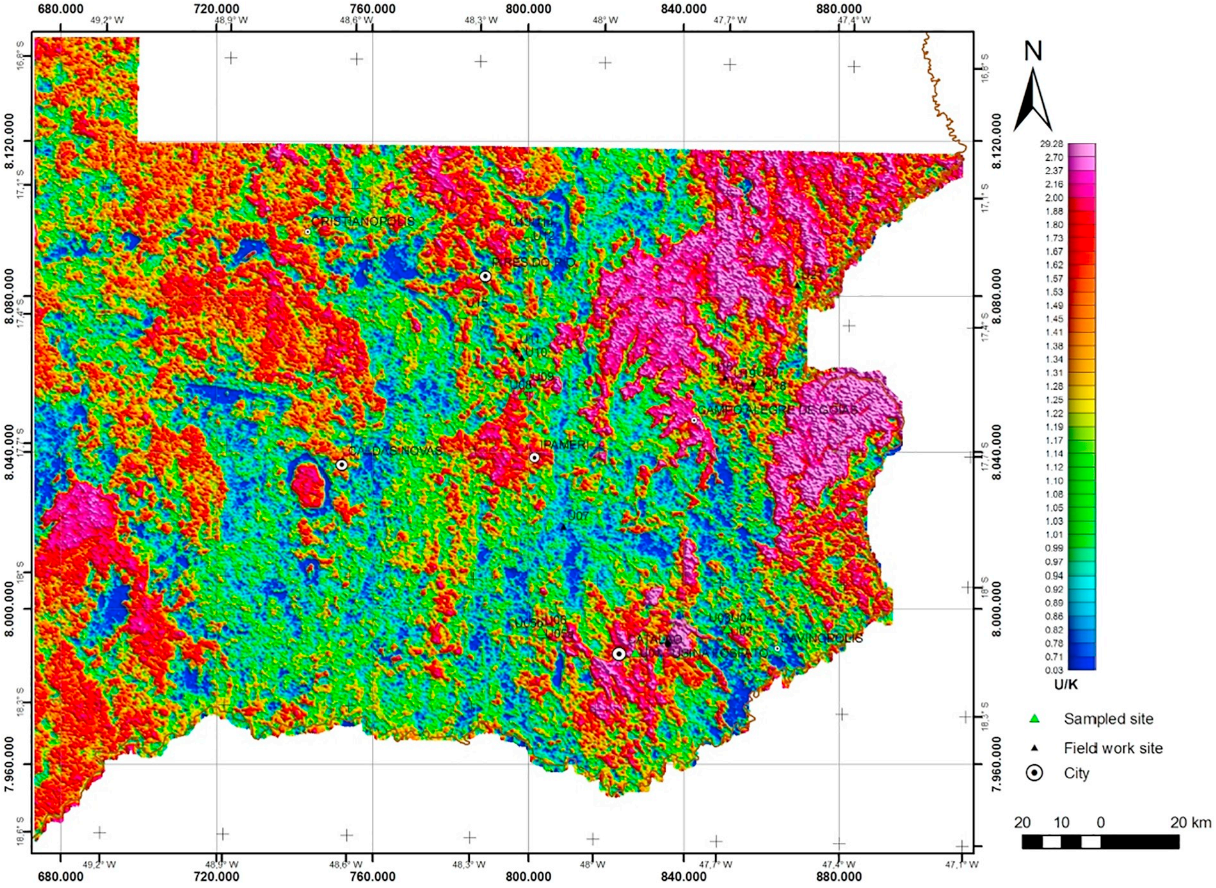

Fig. 9. eU/K ratio map.

$$E = 1.505K + 0.653eU + 0.287eTh \quad (4)$$

where: K, eU and eTh correspond to the apparent concentrations of these elements defined during ground testing.

1.7. Geophysical maps

Aerogeophysical data were processed and interpolated with a regular grid size of 125 m, with subsequent generation of the following products: equivalent uranium map (Fig. 5), equivalent thorium map (Fig. 6), potassium map (Fig. 7) map of the eTh/K (Fig. 8), map of the eU/K ratio (Fig. 9) and the map of analytical signal amplitude of the magnetic field - ASA (Fig. 10). Data processing was performed using Oasis Montaj™ software, version 7.1 (Geosoft, 2009). In the study area, the three radioelements maps show continuous regions with high concentrations. For example, the uranium map (Fig. 5), in its west and central portions, shows a continuous region with high concentrations of this radioelement.

2. Methodology

The estimated concentration rates of the radioelements recorded by the airborne survey data vary significantly in the area. Uranium presents a minimum content of 0.001 ppm and reaches a maximum of 62.4 ppm (Fig. 5). Thorium contents range from 0.002 ppm to 535.49 ppm (Fig. 6). Potassium has a minimum concentration of 0.04% and a maximum value of 8.79% (Fig. 7). Considering the wide variety of geological environments and lithotypes, the quantification of the geological background for this radioelement is relevant in the process of identification of anomalous uranium contents.

The subdivision of the aerogeophysical database by geological environments or by lithotypes could be an appropriate procedure (IAEA, 2003; Curto et al., 2012). However, this procedure is impractical for the specific case, given the large extent of the area and the variety of lithological units. As a solution, in the present study we applied multiple linear regression analysis to highlight anomalous concentrations of uranium, in various lithotypes occurring throughout the study area.

In the present problem, our interest lies on the estimation of anomalous uranium contents by removing the lithological background. Therefore, the anomalous uranium content is the variable to be estimated in the area. The available airborne geophysical variables are the equivalent estimates of uranium, thorium, potassium, the total radiation count, and the intensity of the magnetic field. Ratios between the radiometrics variables can also be estimated for the area.

The simple or multiple linear regression, between the estimated concentrations for uranium, can be used to model and remove the effects of geological processes within different lithotypes (IAEA, 2003). The regression model is subtracted from the data within each unit, or set of units, and the residuals are spatially analyzed. The method is useful for removing gross systematic changes in radioelement concentrations or, in other cases, for highlighting values that differ from the mean distribution of radioelements contents within an interpreted unit (Pires, 1995; Wellman, 1998; Curto et al., 2012).

We are interested in investigating the presence of a statistically significant tendency between uranium and the other geophysical variables. In the regression model, uranium will be our dependent or regressed variable. The other geophysical variable (or variables) will be our independent or regressor variable (or variables).

Therefore, in order to obtain reasonable results to solve our problem, we expect to find significant statistical relations between uranium and the other geophysical variables. Also, we expect that other geophysical parameters, considered as independent variables, should be able to reflect the lithological variation observed in the study area.

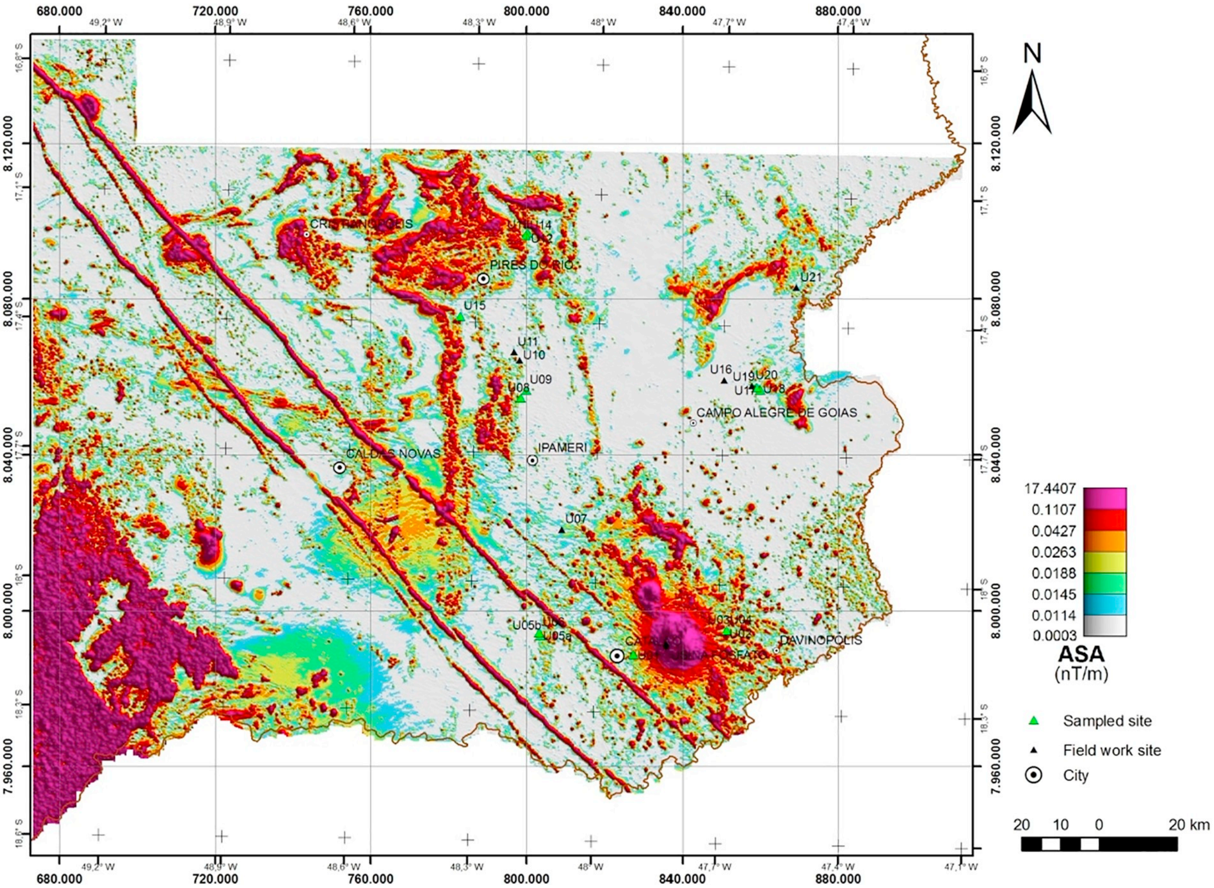

Fig. 10. Analytical signal amplitude map - ASA derived from the anomalous magnetic field - CMA.

Due to its low mobility in the surface environment, thorium is considered as a good lithologic mapper (Pires, 1995). Potassium, although having greater mobility, has an expressive presence in the crust as an important major element of rock-forming minerals and, therefore, indicates a varied distribution of lithotypes at the surface (IAEA, 2003).

The process of obtaining the ratios between radioelement channels eliminates the multiplicative effects occurring simultaneously in the individual channels. The effects of environmental factors on radiometric responses such as vegetation, soil moisture and topography are less evident in the ratios. In this way, the ratio maps present better correlation with the surface geology (IAEA, 2003; Minty et al., 2009; Minty, 2011).

Visual comparison between the geological map of Fig. 2 and the radiometric products allows us to observe the correlation of geological units with features present in radioelement maps (Figs. 5, 6 and 7) and their ratios (Figs. 8 and 9).

The distribution of magnetic intensity also shows, in part, the pattern of the lithotypes present in the earth's crust. Magnetometry has traditionally been used as an important auxiliary tool for geological mapping because the magnetic map of the residual field reflects magnetic sources close to the surface to depths of a few tens of kilometers (Gunn et al., 1997). Therefore, these data do not necessarily reflect surface geology. Additionally, the magnetic anomaly pattern is made complex by the orientation of the induced magnetic field and by the presence of residual magnetization. Magnetic anomalies are then not normally coincident with their sources. However, in areas of outcropping crystalline basement with almost vertical contacts and induced magnetization, reduced-to-the-pole magnetic anomalies correlate with the limits of the magnetic units.

In low and middle latitudes, the analytical signal amplitude can present better results. In the present study, the analytical signal amplitude was used to characterize the lithotypes surface distribution. Considering that the analytical signal amplitude is obtained from the magnetic field derivative in the x, y, and z directions, the shallower magnetic sources are enhanced by better reflecting the surface variation of lithotypes in the study area (Nabighian, 1972). The correlation of features in the analytical signal map with the geological units is evident through the visual comparison of Figs. 5 and 10.

From the points stated above, it is possible to conclude that the radiometric elements, their ratios and the ratio to the amplitude of the analytical signal of the earth's magnetic field, reflect lithological compositions and could be used as mapping tools. As stated before, in the present study we have considered these parameters as our independent variables.

At this point, we should investigate the existing dependency between uranium and our independent variables. Simple regression analysis of uranium concentration to the other radioelements, the ratios and the analytical signal amplitude allowed to evaluate the significance of the linear relations obtained (Fig. 11). The results indicate that, in the study area, the regression is statistically significant in uranium to thorium ratios, eTh/K ratio, eU/K ratio and analytic signal amplitude. This analysis was performed using the original channel values and repeated with the values of the variables normalized by the mean. There was no statistically significant change between the two procedures.

The normalization of uranium contents, dependent variable, by thorium concentration, eTh/K, eU/K and the analytical signal amplitude, our independent variables, has produced an effect of reducing the lithological dependence reflected by the four parameters. Based on these results, a multiple regression model can be constructed.

The estimated uranium content, obtained from the multiple regression model, will have less dependence on the lithology of the area by better reflecting the characteristic background variations of each

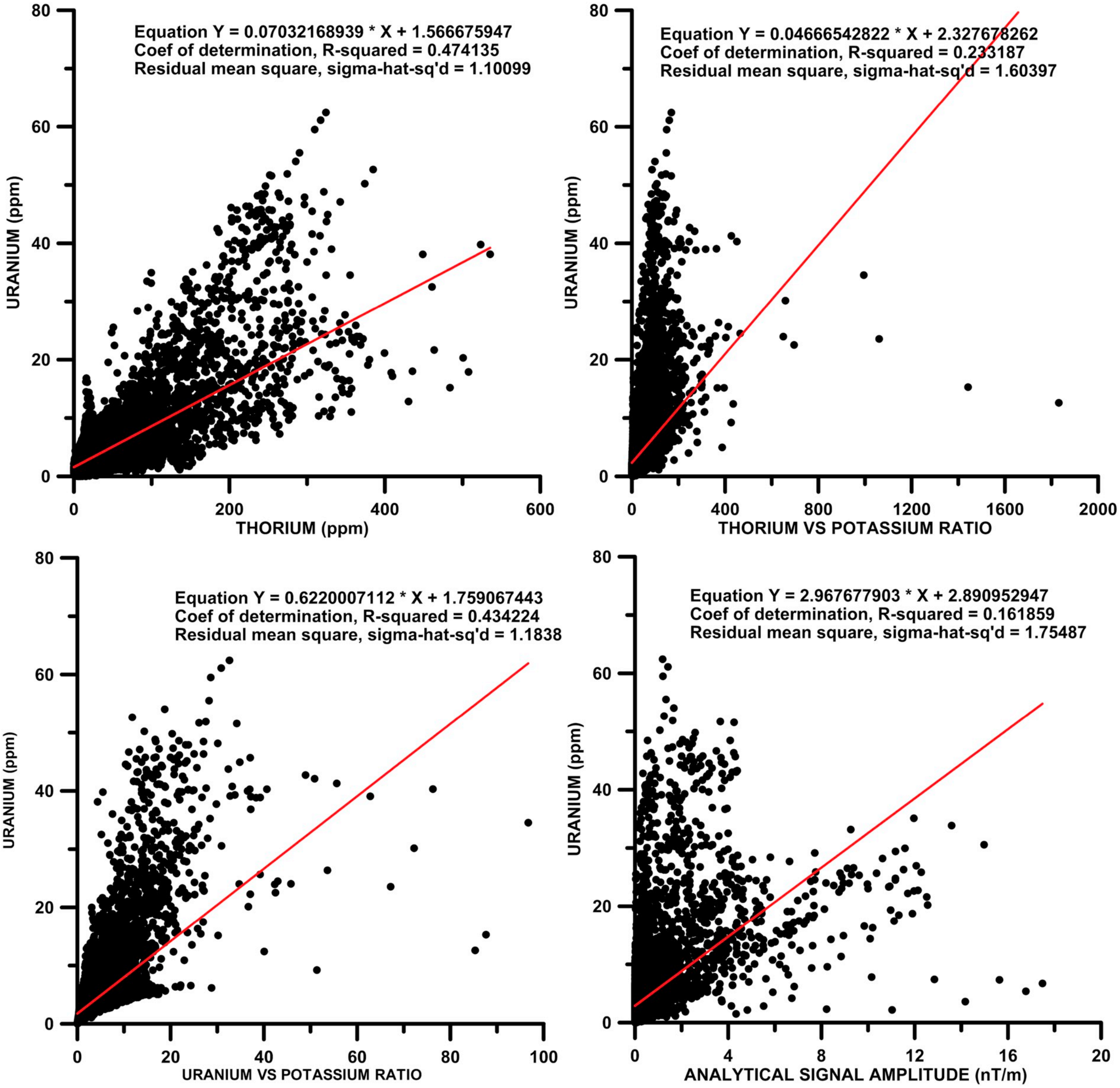

Fig. 11. Scatergrams and linear regression analysis of uranium versus other variables.

geological environment.

For the specific area under study, the linear equation (Eq. (5)) obtained with the least squares model for the estimated uranium (Uest) ratio with the cited parameters was:

$$\mathrm{Uest} = 0,\, 569 + 0,\, 0936\, eTh – 0,\, 123\, eTh/K + 1,\, 14\, eU/K + 0,\, 465ASA \tag{5}$$

This function presented an R^2 goodness of fit index of 83.9%. This result implies that the estimated uranium contents are very close to the original measured uranium contents. The multiple regression model allows the calculation of estimated uranium contents that will have less influence of the lithological variations.

The subtraction of the uranium values obtained during the aerial survey of those estimated for the radioelement by using the multiple regression model, provides the deviations. The deviations map allows the spatial recognition of areas with both positive and negative uranium concentrations, independently of the distribution of surface lithotypes.

3. Results

The method described above was applied to the area covered by the aerial survey. Uranium concentrations above local background were highlighted in several sites and different geological environments (Fig. 12). The highest concentrations are located in the regions of Catalão, southeast portion of the study area, Campo Alegre de Goiás, in the central-eastern part, and in an approximate NNW belt near Ipameri and Pires do Rio municipalities.

In order to confirm the high uranium concentration at the potential targets identified by the presented method, anomalous sites were selected for field inspection, including rock sampling for uranium content estimation by geochemical analysis and also by measurements with a calibrated portable gamma-ray spectrometer. These estimations are presented below for each target.

The most prominent anomalies are associated with the Catalão I Complex (Fig. 13). The high levels observed in the region of Catalão I Complex are linked to the phosphate mining area, the waste disposal areas, the loading area and the ore concentrate (phosphate) pile. Measurement with portable gamma-ray spectrometer and geochemical analysis of sample collected from the phosphate ore concentrate pile revealed uranium contents of 29.4 ppm and 25.1 ppm, respectively.

In this region, high concentration of uranium associated with the Ipameri granite, located about 18 km east of the Catalão I Complex, is

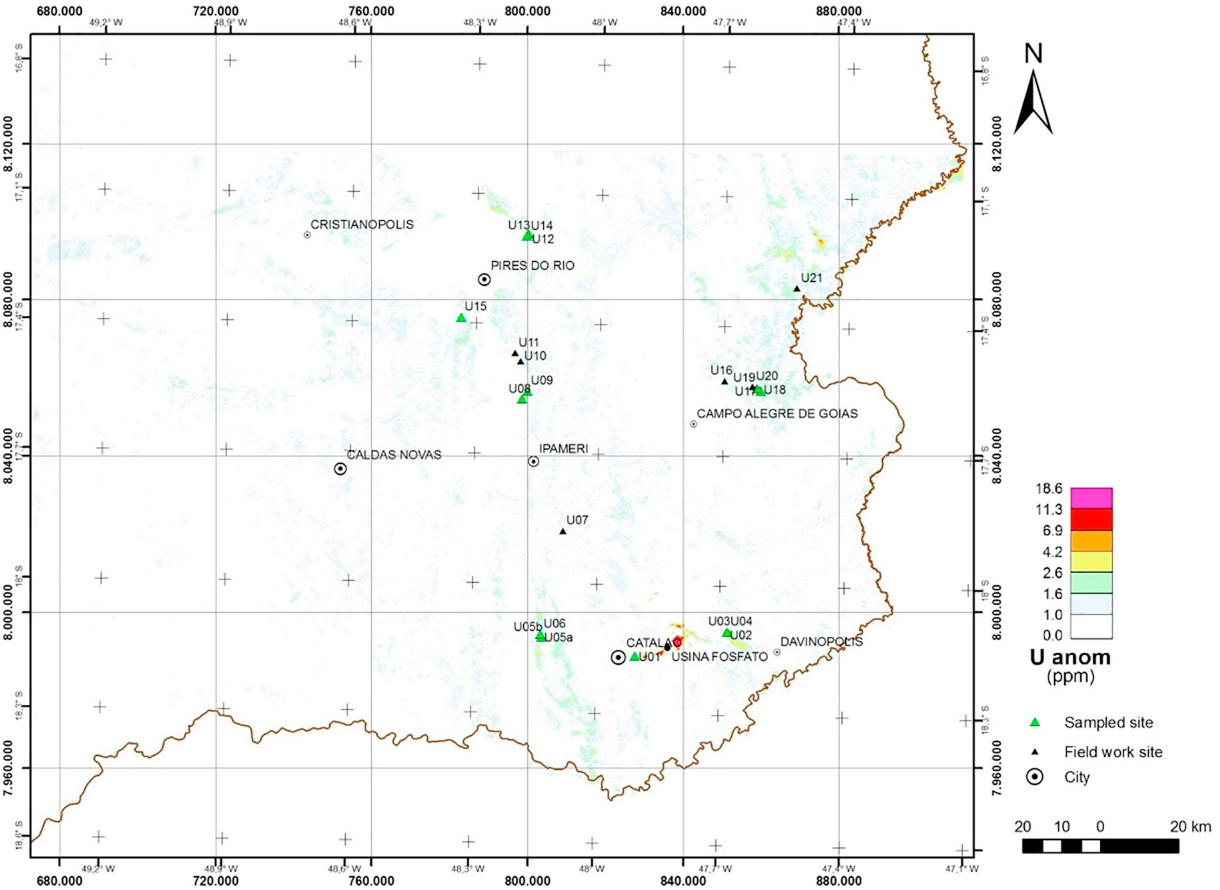

Fig. 12. Positive deviations of uranium contents for the study area. The concentration is in ppm above the local background value. Targets visited and sampled are indicated on the map.

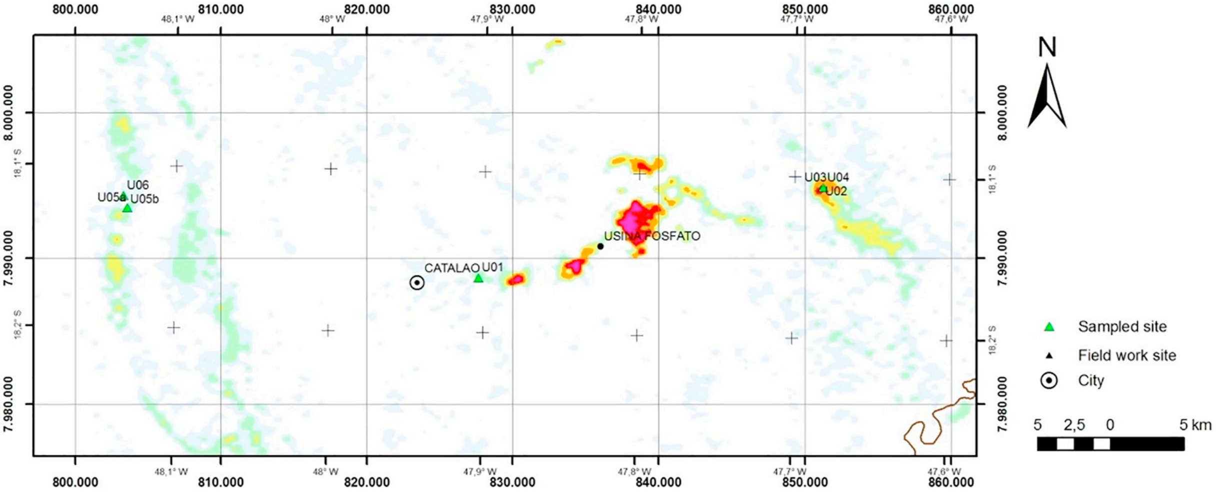

Fig. 13. Detailed map of the uranium content enhancement in the Catalão region. Sample locations are indicated on the map (U01 to U06).

observed. Geochemical analysis of this granite revealed a uranium content of 15.9 ppm. The portable gamma-ray spectrometer recorded 19.6 ppm.

In a target located about 20 km west of Catalão, samples presented uranium contents of 10.1 ppm using geochemical analysis. Local measurement with portable gamma-ray spectrometer indicated a concentration of 20.3 ppm.

Five samples were collected on selected targets in the region between Ipameri and Pires do Rio (Fig. 14). The uranium contents obtained by geochemical analysis for these samples ranged from 3.5 to 10.8 ppm. Measurements with portable gamma-ray spectrometer indicated levels ranging from 3.8 to 11.4 ppm.

In the center-east portion of the study area, Campo Alegre de Goiás region, samples presented uranium contents varying from 3.8 to 8.7 ppm in geochemical analysis and from 10.9 to 13.6 ppm in portable spectrometry (Fig. 15).

4. Discussion and conclusions

The proposed methodology allows for the automated evaluation of

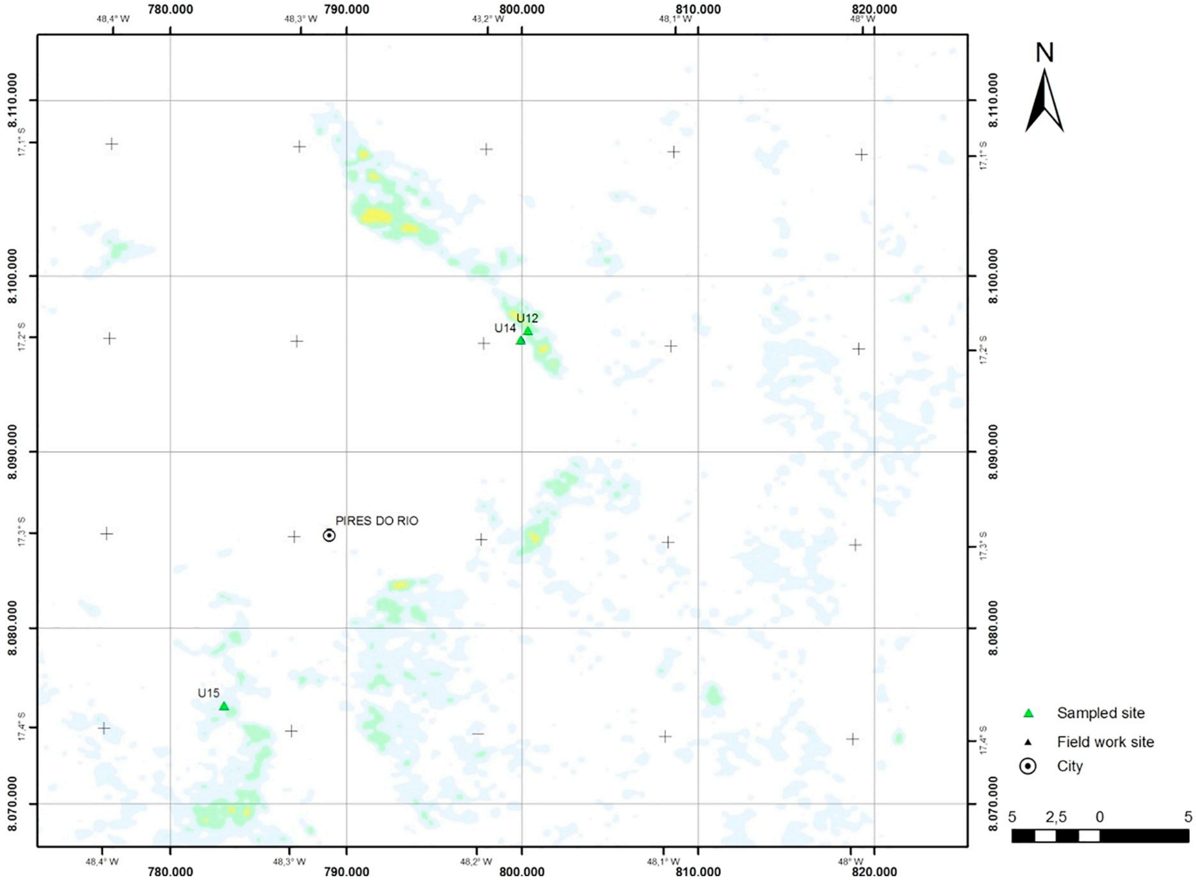

Fig. 14. Detailed map figure of the uranium content enhancement in the Ipameri-Pires do Rio region. Location of samples is indicated on the map (U12 to U15).

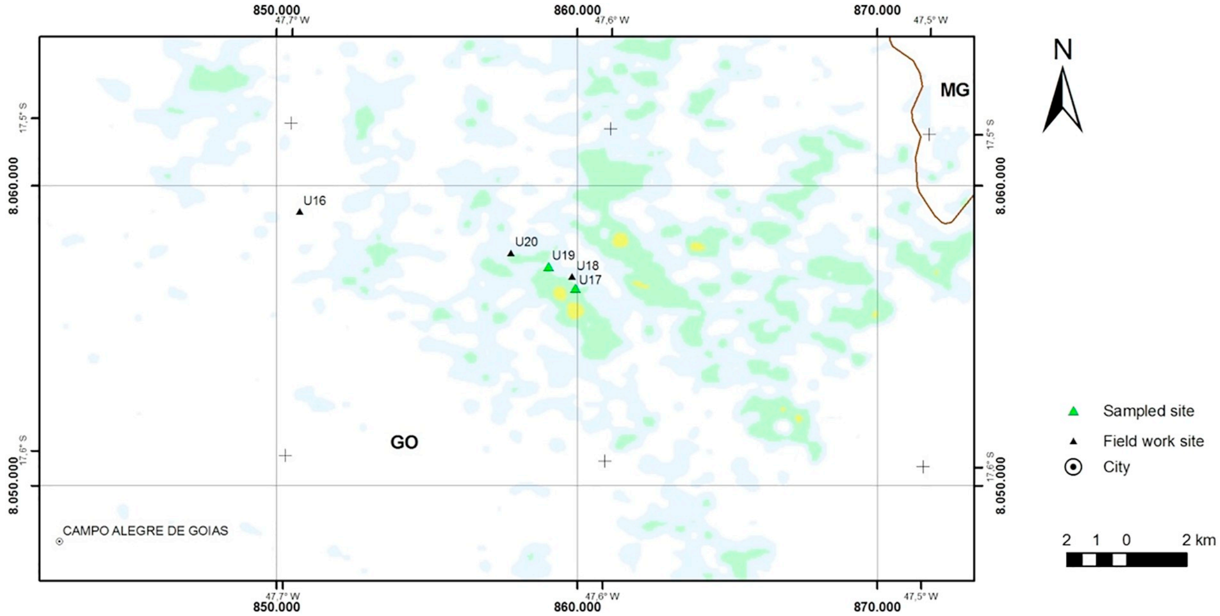

Fig. 15. Detailed map figure of the uranium content enhancement in Campo Alegre de Goiás Region. Sample locations are indicated on the map.

large areas with complex geology for the identification of uranium concentrations above the lithological background. This is achieved by producing an enhancement of anomalies via background subtraction of the latter as a function of the lithotypes.

The comparison between the uranium content map produced with aerial survey data, (Fig. 5) and the map of uranium deviations (Fig. 12), produced after removal of lithological background, shows a drastic spatial reduction in the distribution of high values of the radioelement. The identification of anomalous values in distinct geological environments is greatly facilitated and significantly reduces the diversity of possible targets for mineral exploration in the study area.

The processing was carried out in an area where identified uranium anomalies were linked to different lithotypes and geological environments. Within areas of selected backgrouds, relevant targets were selected for uranium exploration.

The results obtained by the application of the proposed method were checked in the field by geochemical analysis of rock samples collected in selected points in the area. In addition, local measurements with a calibrated portable gamma-ray spectrometer were conducted at the same sampled sites. In all field analyzes, uranium content was higher than the mean background values for these sites.

The geological significance of the regression relationships expressed by Eq. (5) was not investigated in detail but are possibly linked to the very nature of the alkaline rocks and the A-type granites found in the regiona and reinforced by the affinity of U to Th. Alkaline rocks generally present a strong tendency to have high magnetic susceptibility, which explains the strong ASA relationship to U. The radioelement potassium (K) is a common element in minerals forming most alkaline rocks and specially in A-type granites.

Our field observations have shown that the positive U residuals found by the present method correspond to both previously known and also unknown high U occurences which are hosted by both alkaline intrusions as well as A-type granites.

The methodological proposal is presented as an important step in the processing of aerogeophysical data, specifically gamma-ray spectrometry and magnetometry, in order to identify areas with uranium concentration above local lithological background, representing a practical prospective tool.

Therefore, during the stage that precedes field campaigns, it is possible to make use of this method to select anomalous target areas of uranium as a function of geographic characteristics or independent variables (potassium, thorium and analytical signal amplitude of the magnetic field). This methodology can be extended to other elements which have geological association with uranium, such as thorium and rare earth elements.

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