# Radiometric Characterization of soils in North-Central Region of Goias and its implications for estimates of crustal radiogenic heat

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## Abstract

In this work we present progress obtained in analysis airborne geophysical survey data for the north-central region of the state of Goiás. It included both aeromagnetic and gamma spectrometric surveys.

Analysis of aeromagnetic data reveals the presence of a large number of magnetic lineaments, indicative of distinct structural features in subsoil layers. The analytic signal values point to the existence of substantial small scale variations related to lithologic changes.

Analysis of radiometric data allowed determination of relative abundances of natural radioactive elements (Uranium, Thorium and Potassium) of the main soil types and subsoil layers The results obtained indicate that most of the common soil types are characterized by Uranium contents of greater than 1ppm. Only argi soil and lato soil are found to have Uranium contents lower than 1ppm. Thorium abundances also have trends similar to those of Uranium. The distribution of Potassium does not follow a similar pattern, but the K/U ratios fall in the expected range of values. On the other hand, the Th/U ratios are higher than normal. This has been considered as indicative of underestimation of Uranium in soil layers of the study area. Systematic differences in sampling depths of gamma rays and non-equilibrium conditions of the radioactive series in soft sedimentary layers are considered to be possible mechanisms.

The results have also allowed determination of radiogenic heat of the main soil types and subsoil layers. Its value varies significantly with the soil types. Thus cambi soil in this region is found to have a mean heat production of 3.32 ± 5.9 $\mu Wm^{-3}$ while that of argi soil is only 0.36 ± 0.3 $\mu Wm^{-3}$. The mean heat production of soil layers at the surface is 0.68 ± 0.4 $\mu Wm^{-3}$. Heat production values of basement rocks are estimated to be more than 1.3 $\mu Wm^{-3}$, after corrections for density changes and non-equilibrium conditions of Uranium series.

## Introduction

The intensities of nuclear radiations in any particular terrestrial environment are in general related to the abundances of natural radioactive elements in rocks and soils of that locality (Adams, 1961; Wilford et al., 1997). Gamma ray spectrometric methods have been widely used in measurements of radioactive minerals in soils and basement rocks (Ex: Adams and Gasparini, 1970). It has also been used for mapping area extent of geologic rock formations associated with such radioactive elements. Examples of such studies carried out in Brazil include the works of Blum et al (2003), Sapucaia (2005).

Measurements of Gamma radiations at ground levels provide information on the abundances of radioactive elements in the top soil layer of <40cm. Nevertheless results of airborne measurements are considered representative of radiometric characteristics of basement rocks beneath the soil cover. The reason is that weathering and surface processes promote large scale interactions between soil cover and basement rocks. Hence results of gamma spectrometric methods have been widely used as supplementary tools in geologic mapping. Examples of such studies carried out in Brazil include Vasconcelos et al (1994), and Maas et al (2003). With the advent of computer processing facilities it has been possible to analyse the results of large scale air-borne radiometric data. In the present work we report progress obtained in analysis of airborne gamma spectrometric data carried in the state of Goiás. The purpose is to map the radiometric characteristics of the soil and estimate radiogenic heat production of subsoil layers on regional scale.

### Geology and Soil cover of the study area

According to earlier geologic studies (see for example, Almeida, 1968; Winge, 1984) the structural province of Tocantins is situated in the region affected by cratonic collision processes during the Brasiliano orogenic cycle. The main structural units are the granitic – gneissic – granulitic blocks (Median Massif of Goiás) of Arquean age, meta sedimentary belts (Araguaia, Uruaçu and Brasília) of early Proterozoic age, the magmatic belt of Goiás of mid Proterozoic age and the volcano sedimentary sequences (believed to be associated with island arc regions) of neo Proterozoic age. A simplified geologic map of the area is given in Figure (1).

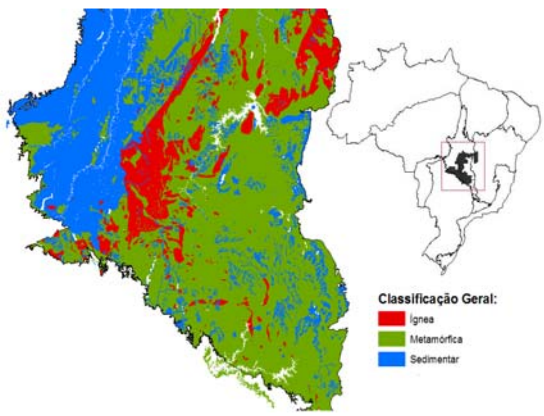


*Figure (1) Simplified geologic map of the study area.*

A number of studies have been carried out for determining the physical and chemical characteristics of soil cover in the study area (EMBRAPA, 2006). The surface features and topography of the study area has also been mapped under the RADAM project of the 1980, by the Ministry of Mines and Energy. More recently, Kerr (2001) has carried out a more detailed analysis of the results of previous studies. Reproduced in the map of Figure (2) are the soil types identified in the study area. Most predominant among these are the Lato soil and Argi soil.

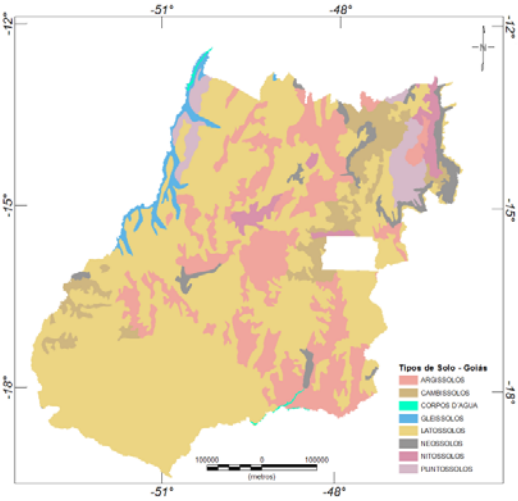


*Figure (2) Map of Soil types in the state of Goiás.*

According to Kiehl (1979) the dominant constituents of soils in the study area are quartz, feldspar and colloidal aluminum silicates. Even though individual mineral densities have mean values of about 2,65x10$^3$ kg/m$^3$ the bulk densities of most of the soils vary between 1.1 and 1.6 (x10$^3$ kg/m$^3$). This is a consequence of the relatively high porosities which vary between 40 a 60%. The mean value of bulk density is 1,5x10$^3$ kg/m$^3$.

**Database**

The data base used in the present work has been acquired as part of a project for acquisition of airborne geophysical survey of the state of Goiás. The data acquisition was carried out during the period of 2004 to 2005 and released since 2010 for academic research by Secretaria de Geologia e Mineração of the state of Goiás (SGM-GO). The survey work was carried out in five stages, in regions described as:

1- Arenópolis arc (including the Juscelândia Sequence);
2- Mara Rosa Magmatic Arc;
3- Western part of Mara Rosa Arc;
4- South Brasilia Belt;
5- North-eastern parts of Goiás.

The locations and area extent of areas covered by the surveys are indicated in the map of Figure (3).

The data sets acquired include measurements of geomagnetic field and intensity of gamma radiation emitted by the radioactive elements of Uranium, Thorium and Potassium. These are recorded in separate channels, along with information on flight altitude and atmospheric conditions. The flight lines were set in north – south direction, has a spacing of 500m and altitude of 100m. Quality control tests were carried out not only prior to data acquisition, but also during and after the surveys.

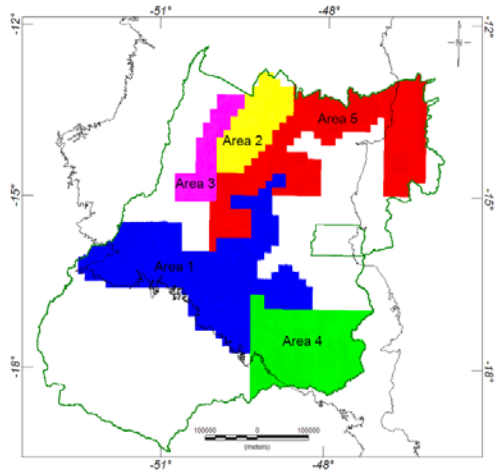


Figure (3) Areas covered in airborne geophysical data acquisitions in the state of Goiás.

**Methodology Used in Data Processing**

Most of the data processing in the present work has been carried out using the computational package GEOSOFT, Oasis Montaj. Initially the raw data were corrected for the perturbing effects of technical survey operations (LAG and Heading effects and altitude variations). In addition, procedures were adopted for filtering, levelling and micro levelling operations, as per standard data processing techniques (see for example, Hood and Ward, 1969; Guimarães and Hamza, 2009). Following this stage a suitable grid system was set up and homogenized data sets derived from the raw data sets for the chosen grid system, using suitable interpolations schemes. The grid size used for interpolations is 125m, which is in accordance with Nyquist criteria. The procedures employed included the method of Minimum Curvature – RANGRID for the geomagnetic data sets and the technique of bicubic splines – BIGRID for radiometric data sets. The unification of data sets was achieved using the standard techniques of *suture* (Geosoft). The aeromagnetic data were further corrected for the effects of diurnal variations of the reference magnetic field.

The radiometric data refer to intensities of gamma rays emitted in radioactive decay of Uranium, Thorium and Potassium. The original data, recorded in units of counts per second (cps), were transformed into values of relative abundances using conversion factors specific to each flight path. These factors depend on the sensitivity and geometry of detectors used and the survey altitude. Finally the values were corrected using calibration data for the particular survey operations. Following this stage radioactive heat production values were calculated from the abundances of radioactive elements.

The procedures adopted are derived from the work of Hamza and Beck (1972) and Hamza (1973). The relevant equation used for this purpose is:

$$H = 10^{-11}\left(9.51 C_U + 2.56 C_{Th} + 3.5 C_K\right) \quad (1)$$

where H is the rate of heat production in units of W/kg, and $C_U$, $C_{Th}$ and $C_K$ are the concentrations of the radioactive elements. It is common practice to express concentrations of Uranium and Thorium in units of parts per million (ppm) and that of Potassium in units of percent (%). The numbers in equation (1) are conversion factors derived from radioactive decay schemes of individual isotopes, described in the earlier work of Hamza (1973). The volumetric heat production values (A) were calculated as the product of heat production per unit mass (H) and the density (ρ) of source material. For mean soil density of 1.5 x $10^3$ kg/$m^3$, the relation volumetric heat production, in units of μW/$m^3$, is:

$$A = 0.1428\, C_U + 0.0383\, C_{Th} + 0.0522\, C_K \quad (2)$$

**Result and Discussion**

***Characteristics of Magnetic Anomalies***

In presenting results for the aeromagnetic survey we focus first on the progress obtained in identification of features present at shallow depths. In this case the standard practice is to outline the magnetic lineaments (deduced from the first derivative of the crustal field). The geographic distribution of the main lineaments identified in the study area is illustrated in the map of Figure (4). The outstanding features in this map are the changes in directions of the magnetic lineaments. In the southern and north eastern parts of the study area the orientations of the magnetic lineaments are predominantly southeast to northwest, whereas the directions are southwest to northeast in the northern and western parts.

The results geologic studies indicate that the direction of structural features in the study area is predominantly south west to northeast. Thus the presence of lineaments of SE – NW direction in the southern parts is product of tectonic activities of neo Proterozoic age or relatively more recent times.

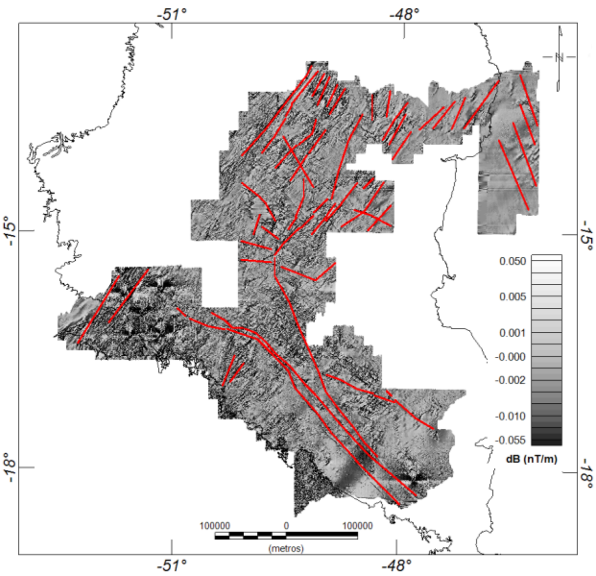


*Figure (4) Magnetic lineaments identified in the study area.*

The spatial distribution of the analytic signal, which is calculated as the modulus of the second derivative in the three directions of the magnetic field provided additional information on the characteristics of structural features in the study area. The technique is often considered as the best for outlining the borders of subsurface bodies with contrasts in magnetic properties. The results obtained indicate that the magnitudes of analytic signal are in the range of -0.9 to 45 nT/m with an average value of 0.03 ± 0.2 nT/m. The wide range in values is an indication that contrasts in magnetic properties occur on local scales in the study area. The map of Figure (5) illustrates the geographic distribution of the analytic signal. Note that the amplitude analytic signal is large in the western and central parts compared to that in the north eastern parts.

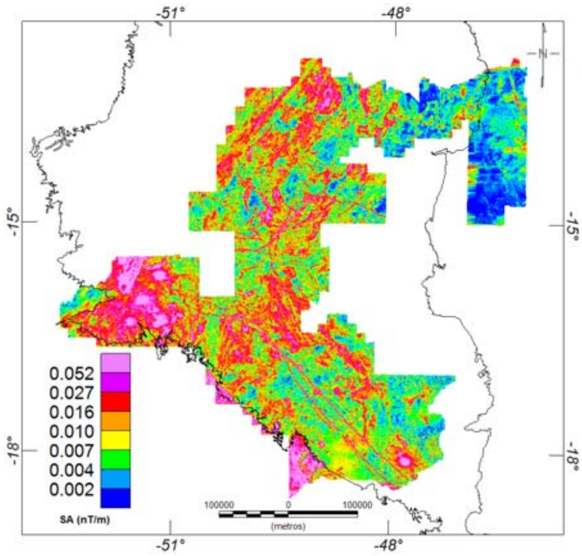


*Figure (5) Amplitudes of analytic signal in the study area.*

***Characteristics of the Radiometric Field***

The mean value of Uranium in the study area is 1.28 ± 1.06 ppm while that of Thorium is 11.4 ± 8.5 ppm. Thus the Th/U ratios are high (>8) indicating either underestimation or depletion of Uranium in surface layers. The mean value of Potassium is 1.2 ± 0.8 % which imply that K/U is of the order of 1x$10^4$, a value typical of crustal rocks. On the other hand the large values of the standard deviations of these elements are indications of substantial variations in the lithologic characteristics of rock formations in near surface layers.

The geographic distribution of Uranium and Thorium abundances are illustrated in the maps of Figures (6) and (7). Referring to Figure (6) we note that Uranium abundances are relatively high in the south eastern and south western parts. Low values appear to be restricted to narrow belts in the central parts. Mixed patterns of low and high values occur in most of the remaining areas. Similar patterns can be seen in the map of Thorium abundances in Figure (7). The non-equilibrium conditions of Uranium series in soils seems have marked effects on the spatial distribution of anomalies. Thus direct correlations with main lithologic units are partially obliterated.

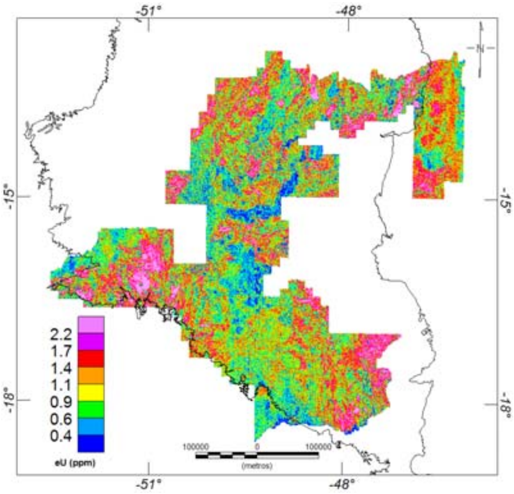


*Figure (6) Geographic distribution of Uranium in the study area.*

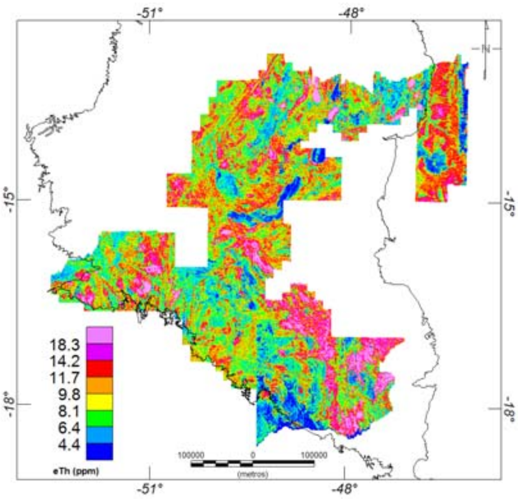


*Figure (7) Geographic distribution of Thorium in the study area.*

The geographic distribution of Potassium abundances, illustrated in the map of Figure (8), reveals a pattern different from those observed for U and Th. Referring to this figure we note that Potassium abundances are relatively high in the south eastern and in several isolated regions in the central parts. Relatively high values are also found along a north-south belt in the north eastern parts. Low to intermediate values are found to occur in most of the remaining areas. As in the case of Uranium and Thorium the overall pattern seems unrelated to the characteristics of geological formations in near surface layers. On the other hand, the correlation of Potassium abundances does not reveal any significant degree of correlation with soil types.

The ternary diagram presented in Figure (9) illustrates the distribution of relative abundances of the three radioactive elements, U, Th and K. The patterns in this figure are quite complex there being no indications of any significant correlations with either geological structures or soil types.

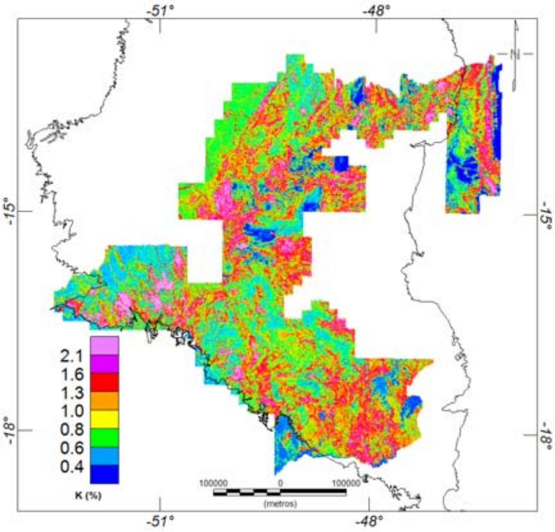


*Figure (8) Geographic distribution of Potassium in the study area.*

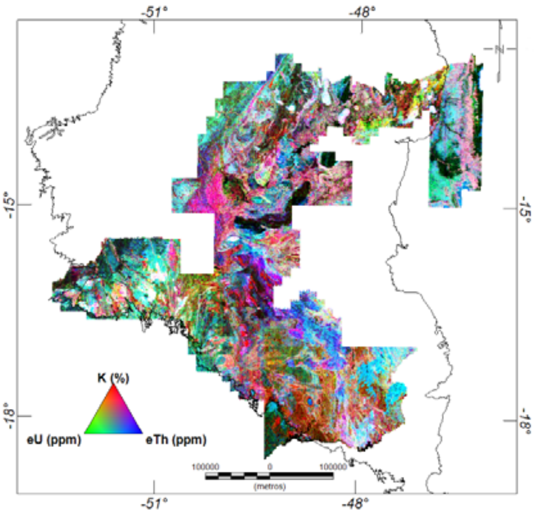


*Figure (9) Ternary diagram of the radioactive elements (uranium, Thorium and Potassium) in the study area.*

***Correlations with Soil Types***

In this item we examine the results relevant to the study of soil types in the study area. This was done by comparing regional scale features present in the maps of abundances of radioactive elements with those of soil types. Superposition of the relevant shape files allowed determination mean values of U, Th and K in the main soil types. The results obtained are presented in Table (1). Note that Plinto soil, Cambi soil, Neo soil, Glei soil and Nito soil are characterized by relatively high values of Uranium and Thorium, when compared with those of Lato soil and Argi soil. The Th/U ratios are in the range of 5 to 10 for all of the soil types, which has been considered as indicative of no-equilibrium conditions of the Uranium series in the study area. Potassium abundances do not follow a similar trend. The possibility that widespread use of potash rich fertilizers have interfered with the results airborne radiometric surveys cannot entirely be ruled out.

Table 1 – Mean and standard deviations of U, Th and K in main soil types of the study area.

| Soil Type | eU (ppm) | eTh (ppm) | K (%) |
|---|---|---|---|
| Plint Soil | 1.46 ± 0.9 | 10.97 ± 6.8 | 0.70 ± 0.7 |
| Cambi Soil | 1.45 ± 1.4 | 11.90 ± 8.3 | 1.48 ± 1.0 |
| Neo Soil | 1.26 ± 1.0 | 8.94 ± 7.1 | 1.17 ± 0.8 |
| Glei Soil | 1.23 ± 0.8 | 10.17 ± 4.4 | 0.96 ± 0.6 |
| Nito Soil | 1.11 ± 0.7 | 11.39 ± 5.9 | 1.24 ± 0.8 |
| Lat Soil | 0.80 ± 0.5 | 4.81 ± 5.2 | 0.75 ± 0.8 |
| Argi Soil | 0.63 ± 0.6 | 5.86 ± 5.8 | 0.92 ± 0.5 |

Though the variations in the abundances of radioactive elements in near surface layers is a problem in mapping radiometric characteristics of basement rocks it has potential applications in classification of soil types. For example, the variations in the abundances of Uranium may be used as a tracer and also as a means of identifying sub classes of soils. As an illustrative example we present in Figure (10) Uranium variations in a segment of Cambi soil in the north eastern part of the study area. Though the overall mean value for Cambi soil is 1.4 ± 1.3 ppm. Such variations are indicative specific changes in compositional structure of the soil, but not readily identifiable by standard procedures in soil classification.

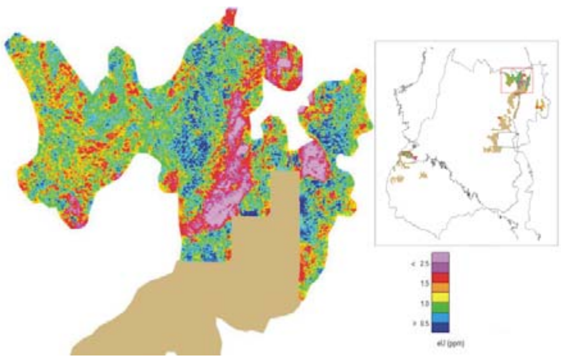

*Figure (10) Variations in the U contents of Cambi soil.*

***Radiogenic Heat***

Abundances of Uranium, Thorium and Potassium calculated from results of airborne radiometric surveys have also allowed determination of radiogenic heat production values for the study area. The procedure adopted here is based on the use of equation (2) and assuming that soils in general have a density of 1.5kg/m$^3$. The weighted mean value of heat production of soils the study area is 0.68 ± 0.4 μW/m$^3$. This value is in reasonably good agreement with the value obtained by Roque and Ribeiro (1998), for core samples of carbonate sequences in shallow boreholes. However these are relatively less than the mean values calculated for a large number of fresh samples collected from outcrops in the study area by Iyer et al (1984) and also values inferred from crustal seismic velocities by Alexandrino (2008) and Alexandrino and Hamza (2010). The geographic distribution of heat production values obtained is illustrated in the map of Figure (11). There are a number area segments in the eastern parts of the study area where heat production is higher than 1μW/m$^3$, the common range of variation being in the interval of 0.2 to 1.2 μW/m$^3$. There are indications that much of the small scale variations are related to variations in lithologic types mapped in geologic studies.

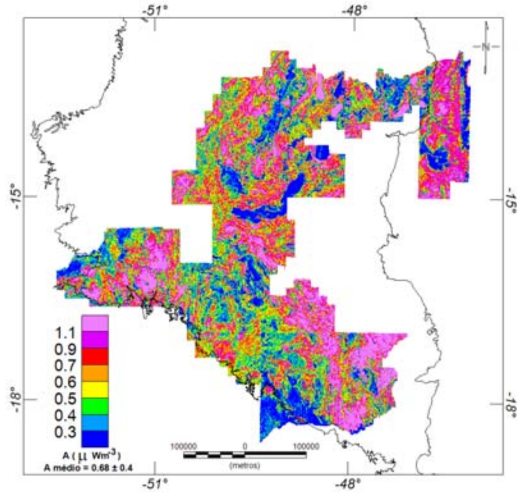


*Figure (11) Distribution of radiogenic heat production in the study area.*

The heat production values calculated for the main soil types and basement rocks are given in Table (2). Most of the soil types have heat production values of less than 0.7μW/m$^3$. The only exception is Cambi soil which has a relatively high value of 3.32 μW/m$^3$.

Table (2) Heat production values of the main soil types in the study area.

| Soil Type | Heat Production (μW m$^{-3}$) |
|---|---|
| Cambi soil | 3.32 ± 5.9 |
| Plinto soil | 0.66 ± 0.4 |
| Nito soil | 0.66 ± 0.3 |
| Glei soil | 0.61 ± 0.3 |
| Neo soil | 0.58 ± 0.4 |
| Argi soil | 0.36 ± 0.3 |
| Lato soil | 0.34 ± 0.9 |

**Conclusions**

In this work progress obtained in analysis airborne geophysical survey data for the north-central region of the state of Goiás has been examined. Analysis of aeromagnetic data reveals the presence of a large number of magnetic lineaments, and a change in direction in the central region of the map, indicative of distinct structural features in subsoil layers. The analytic signal values point to the existence of substantial small scale variations related to lithologic changes.

The analysis of gamma spectrometric data has allowed determination of relative abundances of natural radioactive elements (Uranium, Thorium and Potassium) of the main soil types and subsoil layers. The results indicate that most of the common soil types are characterized by Uranium contents of greater than 1ppm. Only argi soil and lato soil are found to have Uranium contents lower than 1 ppm. Thorium abundances also have trends similar to those of Uranium. However, the Th/U ratios are higher than normal, indicating depletion or underestimation of Uranium in soil layers of the study area. The possibility that low Uranium contents arise from non-equilibrium conditions of the radioactive series in soft sedimentary layers is considered to be the most likely mechanism.

The results have also allowed determination of radiogenic heat of the main soil layers. Its value varies significantly with the soil types. Thus Cambi soil in this region is found to have a mean heat production of 3.32 ± 5.9 $\mu W m^{-3}$. The Cambi soil is characterized as being well drained, shallow and with high silt. Heat production of argi soil is 0.36 ± 0.3 $\mu W m^{-3}$. This soil type is known for the ease of fertilization and development of native vegetation, because of its good drainage and the fact that it is moderately acid. The mean heat production of soil layers at the surface is 0.68 ± 0.4 $\mu W m^{-3}$.

The heat production values for basement rocks were calculated after corrections for the non-equilibrium conditions of Uranium series and density changes. The estimated mean value is 1.3 $\mu W m^{-3}$. This value is in reasonable agreement with results obtained by Iyer et al (1984) using Pb – Pb and isotope mass spectrometry techniques.

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