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STATISTICAL CHARACTERIZATION OF GREENSTONE SEQUENCES USING MAGNETIC AND "GAMMA-RAY SPECTROMETRIC DATA, GUARINOS-PILAR DE GOIÁS AREA, BRAZIL

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RESUMO CARACTERIZAÇÃO ESTATÍSTICA DE SEQÜÊNCIAS *GREENSTONE* UTILIZANDO DADOS MAGNÉTICOS E ESPECTOMÉTRICOS DE RAIOS-GAMA, ÁREA DE GUARINOS-PILAR DO SUL, BRASIL. Diversos depósitos no mundo inteiro estão correlacionados a seqüências do tipo *greenstone*. No Brasil, essas seqüências apresentam ocorrências de ouro, prata, cobre, níquel, talco, ferro e manganês. A identificação dessas seqüências do tipo *greenstone* é, portanto, um passo importante na prospecção mineral. A aplicação de método estatístico de classificação de amostras, em dados aéreos magnéticos e gamaespectrométricos, da região de Guarinos-Pilar de Goiás, permitiu a identificação das principais feições geológicas. A interpretação integrada dos dados magnéticos e gamaespectrométricos produziu melhores resultados do que aqueles obtidos usando somente a informação espectrométrica. Os melhores resultados foram obtidos com a utilização das mudanças no padrão magnético, ao invés da intensidade do campo total, conjuntamente com os dados de gamaespectrometría. Com o uso de análise de agrupamentos do Modo-G foi possível identificar a sequência do tipo *greenstone,* pertencente ao Grupo Pilar de Goiás, e separar sua componente metassedimentar das metavulcfinicas. Como as unidades da seqüência tipo greenstone apresentam-se mineralizadas em locais da região, o procedimento usado neste trabalho pode auxiliar a prospecçSo mineral, pelo estabelecimento de alvos prioritários.

Palavras-chaves: Raios gama, espectometria, greenstone, análise de grupos.

ABSTRACT All over the world, many mineral deposits are related to greenstone sequences. In Brazil, these greenstone sequences show gold, silver, copper, nickel, talc, iron and manganese mineralizations. Therefore, identification of greenstone sequences is an important step in mineral exploration programs. More man 50% of Brazilian territory is covered with airborne magnetic and gamma-ray spectrometric data. Interpretation of these data can improve me geological knowledgement. Application of a statistical classification method on magnetic and gamma-ray spectroinetric data from the Guarinos-Pilar de Goiás area allowed identification of the main geological units. Integrated interpretation of magnetic and spectrometnc data supplied better results than those obtained using only the gamma-ray information. The best results were obtained by using the changes in magnetic pattern rather than the total field intensity. With G-mode cluster analysis it was possible to discriminate the existing greenstone sequence and to separate its metasedimentary unit from metavolcanic units. Results indicate areas with no correspondence between statistical groups and mapped geology. These areas should be investigated by field work. Greenstone units identified by the statistical procedure are known to be mineralized. Therefore, the method could be used in guiding mineral exploration programs in the region.

Keywords: Gamma-ray, spectometry, greenstone, cluster analysis.

INTRODUCTION Throughout the world, many mineral deposits can be correlated to greenstone sequences. In Brazil, these sequences are found in Archean and lower Proterozoic terrains. Deposits of gold, silver, copper, nickel, talc, iron, and manganese have been discovered associated with them (Schobbehhaus & Campos 1984, Bernasconi 1985).

Identification and mapping of greenstone belts are important steps in mineral exploration programs in Brazil. The use of geophysical information can save significant amount of time especially when dealing with little known areas. The interpretation of geophysical data can lead to a better knowledge of the geological setting and the establishment of exploration procedures for a specific region.

Since the early 1950's the Brazilian Government has, through several agencies, been conducting airborne geophysical surveys. Presently, aerial magnetic and gamma-ray surveys have been done over nearly fifty percent of the country. A few areas, in the states of Goiás and Bahia, have also been investigated with airborne eletromagnetic systems. Results of these surveys are available in maps and profiles at varying scales (Barros 1984).

There are just a few areas in Brazil where the geology is known at a scale equal to or larger than 1:1.00,000. In more than sixty five percent of the country the available maps have 1:250,000 or smaller scales. Mineral exploration programs generally ask for detailed geologic maps. In this paper, I show how to use existing geophysical information in identifying greenstone sequences and sketching the geology of areas suitable for mineral exploration. For the present purpose, I analyse an area in the state of Goiás, in Central-Western Brazil, known to have mineralized greenstone sequences (Ribeiro Filho & Teixeira 1980, Lacerda 1986, Danni 1988). The results show a better lithology identification than those obtained by Barreto & Vieira (1986), working with a similar data set for a nearby region.

The use of multivariate statistical analysis, on the magnetic and gamma-ray spectrometric data of the Guarinos-Pilar de Goiás area, allows the interpreter to identify the main geology units. This method discriminated the known greenstone sequence and separated its metasedimentary unit from the metavolcanic units. It is well known that, in the region, the gold deposits of Fazenda do Prefeito, Chapéu de Sol and Pilar de Goiás are associated to metasedimentary greenstone belt units (Kuyumjiam 1981, Branco 1984). The procedure discussed in this paper can, therefore, be used in helping to establish gold prospects in the Guarinos-Pilar de Goiás region.

THE GUARINOS-PILAR DE GOIÁS AREA The Guarinos-Pilar de Goiás study area is located in the state of Goiás in Central-Western Brazil (Fig. 1). The first detailed studies in the area were conducted by Barbosa *et al.* (1969). Danni & Ribeiro (1978), Lacerda (1985), and Danni (1988)

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presented more detailed information on the geology of the study area.

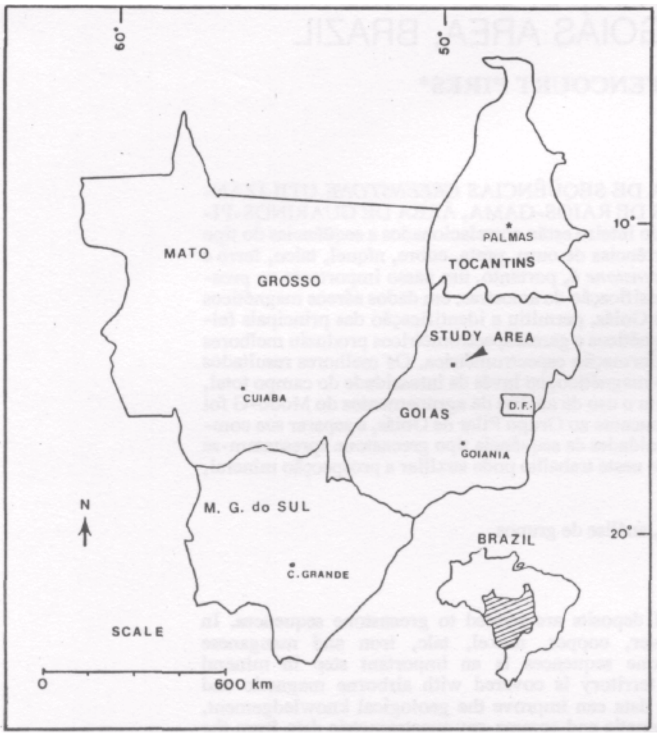

Figure 1 — Location map of the Guarinos-Pilar de Goiás study area

Figura l - Mapa de localização da área de Guarinos-Pilar **de Goiás**

Geological setting The study area lies within a Pan-african mobile belt developed between Guaporé and São Francisco Archean cratons. It is certain the region has been involved in two orogenic episodes: the Uruçuano cycle (1,400 Ma - 1,100 Ma) and the Brasiliano cycle (700 Ma-450Ma). The rocks in this region may also have undergone alterations during th earlier Transamazonian cycle (2,100 Ma-1,800 Ma) *(Danni et al.* 1982).

There are three major tectono-stratigraphic units in the region: the granite-gneiss complex, the greenstone belts of Pilar de Goiás Group, and the Araxá Group. The first two units are of Archean age while the Araxá Group belongs to the middle Proterozoic (Fig. 2). Detailed characterization of these units have been presented by Danni & Ribeiro (1978), Lacerda (1985), and Danni (1988).

The granite-gneiss complex is represented in the area by three blocks: the Rio Caiamar, the Cedrolina, and the Rio Muquem (Danni & Ribeiro 1978).The first block lies in the western portion of the study area. It is mainly composed of leucocratic gneiss with discrete foliation, sometimes truncated by localized quartz-feldspar remobilizations. The most common gneiss in this block is biotite-gneiss with granodiorite composition. The occurrence of metamorphosed gabbro intrusions is observed here also (Fig. 2). The Rio Muquem block is located in the central portion of the study area. It consists of gneiss with strong foliation represented by the lineament of biotite and microline-orthoclase megacrystals. This block is also intruded by amphibolitized gabros (Danni & Ribeiro 1978, Lacerda 1985). The Cedrolina block is situated in the northeastern corner of the study area (Fig. 2) and has a more complex lithology (Danni & Ribeiro 1978). Muscovite biotite gneiss is the predominant lithology. The gneiss is often interbedded with feldspar-garnet-biotite schist, muscovite schist, staurolite-kyanite-garnet-muscovite-biotite schist, and migmatite (Lacerda 1985).

The Pilar de Goiás group encompass three units lying over the granite-gneiss complex. These north west-southeast trending units are narrow and conditioned to tectonic depressions in the basement. A metasedimentary unit is the largest of the three units, as shown in figure 2. It is formed by

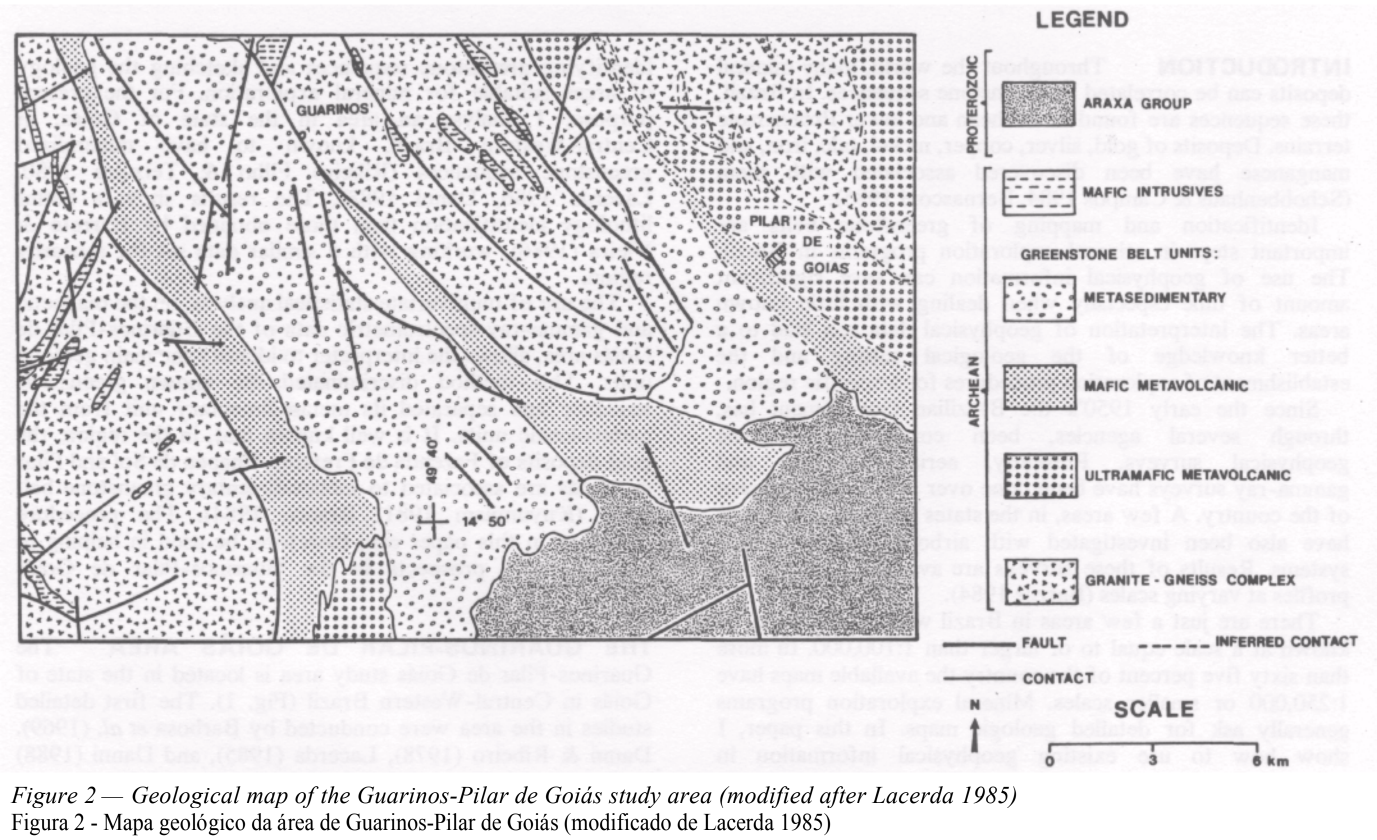

Figure 2 — Geological map of the Guarinos-Pilar de Goiás study area (modified after Lacerda 1985)

Figura 2 - Mapa geológico da área de Guarinos-Pilar de Goiás (modificado de Lacerda 1985) graphite-chlorite-sericite schist, magnetite-muscovite schist, hematite-muscovite schist, quartz-muscovite schist, muscovite-chlorite schist, and garnet-muscovite-biotíte quartz-schist. A metavolcanic mafic unit flanks the metasedimentary unit (Fig. 2). This mafic unit has amphibole schist, quartz-feldspar schist, hornblende-chlorite-biotite schist, chlorite schist, and talc schist. A metavolcanic ultramafic unit occurs in the study area in smaller portions located in the south and northeast, as shown in figure 2. This unit comprised serpentinites, talc-tremolite schist, tremolite-serpentine schist, talc-chlorite schist, quartz marbles, and quartzites (Lacerda 1985).

The Araxá Group is present in the southeast portion of the study area (Fig. 2). It is formed by muscoyite-biotite schist, garnet-muscovite-biotite schist, feldspathic schist, and quartzites (Danni & Ribeiro 1978).

Mineral deposites of asbestos, gold, talc, copper, and kyanite occur hi the study area. Except for the kyanite deposit, wich is related to granite-gneiss complex, all deposits occur in the greenstone sequences of the Pilar de Goiás Group.

Geophysical data The Guarinos-Pilar de Goiás study area is a small portion of the region covered by the Brazil/Canada Geophysical Project. This project, conducted in the late 1970's, carried out ground and airborne geophysical investigation of a large area (Carmo 1978). Airborne magnetic and gamma-ray spectrometric surveys covered areas from the states of Goiás, Mato Grosso, Maranhão, and Pará, totaling 375,000 km^2 (Schmaltz 1981).

The flight lines were flown north-south with a separation of 2 km. Some areas were flown with 1 km spacing. For the area under study, gamma-ray and magnetic maps in 1; 100,000 scale are available. Stacked profiles containing gamma-ray spectrometric results were published for each flight line.

For this study I obtained the gamma-ray spectrometric data by digitizing stacked profiles corresponding to 15 flight lines, with an average 2 km spacing, covering the area. The total magnetic field intensity data was obtained by digitizing the existing 1:100,000 map for points corresponding to the flight lines used in obtaining the gamma-ray data. It should be clear that, by using north-south flight lines spaced 2 km apart, it will be difficult to interpreted geological structures like the thin stripes trending north west-southeast (Fig. 2). The distribution and number of the flight Unes used in this study are presented in figure 3.

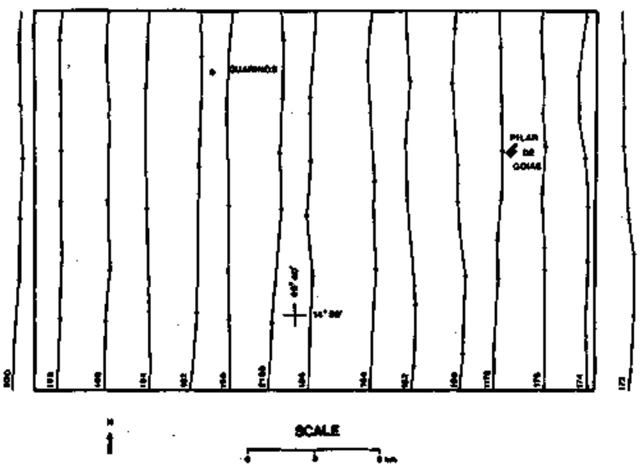

Figure 3 — Location and identification of geophysical flight lines at the Guarinos-Pilar de Goiás study area
Figura 3 - Localização e identificação das linhas de vôo geoffsico na área de Guarinos-Pilar de Goiás

With the digitizing process 52 equally spaced samples were obtained along each flight line. Each sample is characterized by the following parameters: equivalent ppm of uranium and thorium (eU and eTh); percentage of potassium (K); total gamma-ray count (TQ; the ratios - U/Th, U/K, and Th/K; and the total magnetic field intensity.

In figure 4, a simplified total field magnetic map for the Guarinos-Pilar de Goiás study area is presented. The existence of three different magnetic signatures can be observed in the area. In regions labeled 1, almost no magnetic relief can be seen. Regions type 2 have strong magnetic relief with several localized anomalies. Region type 3 have strong magnetic relief with a clear southwest-northeast trend. Comparing figure 4 with the geologic map, we see the correspondence between magnetic regions and geologic units. To each of the previously obtained sample a parameter corresponding to the magnetic signature was added. This parameter could assume the values 1,2 or 3 depending on to which region the sample belonged. With the inclusion of the magnetic signature, I ended with nine parameters for each of the 52 samples representing a flight Une.

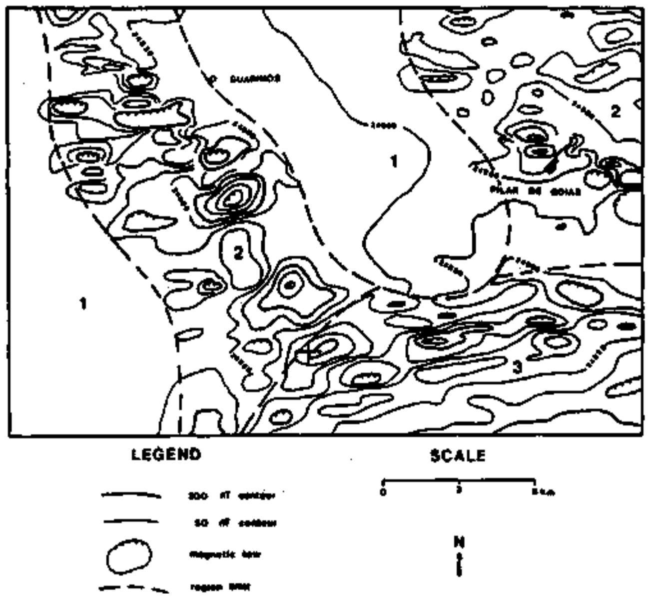

Figure 4 — Magnetic map of the Guarinos-Pilar de Goiás study area (simplified after Ministério das Minas e Energia 1978)
Figura 4 - Mapa magnético da área de Guarinos-Pilar de Goiás (simplificado do Ministério de Minas e Energia 1978)

Another way of using the magnetic information into the clustering procedure could be by inverting the field data for magnetic susceptibility. The values obtained would be used as one of the parameters characterizing each sample. Since magnetic field reflects lithologic and structural changes with depth, care should be taken when using it for mapping surface geology. For the Guarinos-Pilar de Goiás area, the magnetic data reflect the surface geology. Other areas may ask for high-pass filtered data.

Data analysis The existence of several parameters for each sample point allows an enormous number of ways of treating the data. The use of statistical techniques, among others, is a natural procedure to interpret the data set.

The values, represented in each sample obtained for the Guarinos-Pilar de Goiás study area, reflect the lithologic units present in the region. Using statistical techniques it is possible to classify these samples into clusters or groups. The groups generated by the statistical method show correlation with the geology of the area.

For the Guarinos-Pilar de Goiás study area, I used the G-mode technique to analyse the geophysical data. This technique was used by the Pires & Harthifl (1989) on the interpretation of gamma-ray spectrometric data from Goiás In this method, the original multivariate distribution is reduced to an univariate quasi-gaussian distribution. This new distribution has a mean equal to zero and a variance equal to one. Since *n* is the total number of objects, $n' < n$ objects, which form the first group, are selected by a test of a suitably defined normal distribution. The procedure is repeated to remaining $n\text{-}n'$ samples to identify the second homogeneous group. With further iterations all the groups can be identified as explained by Coradini *et al.* (1977).

RESULTS Initially I applied G-mode clustering method to the gamma-ray spectrometric data. Following Pires & Harthill (1989), I used G-mode analysis on the data condering only the U, Th, K, and TC values; only the U/Th, U/K, Th/K ratio values; and finally all seven spectrometric values together.

The clustering results obtained when considering only the U, Th,K and TC values show no correpondence with the mapped geology of the study area. The results using the ratios and those for all seven values are shown, respectively, in figures 5 and 6.

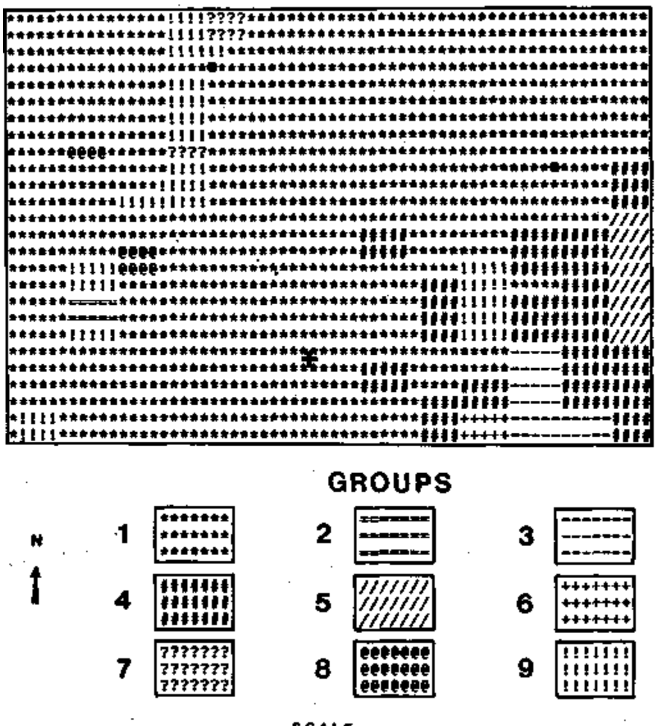

Figure 5 - Clustering results using gamma-ray spectrometric ratios (U/Th, U/K and Th/K) as parameters in each sample. Location ofGuarinos (W) and Pilar de Goiás (E) indicated by dots. Cross indicates point with 49° 4ff longitude and 14° 50′ latitude

Figura 5 - Resultados do agrupamento usando as razões gama-espectrométrícas (U/Th, U/K e Th/K) como parâmetro em cada amostra. Localização de Guarinos (W) e Pilar de Goiás indicada por pontos. A cruz indica o ponto de longitude 49° 40' e latitude 14° 50'

The clustering technique when applied on the gamma-ray ratios produced nine different groups (Fig. 5). By comparing these results with the geological map, it can be observed that clustering produced groups that partially correspond to mapped geologic features. Groups 2, 7, 8, and 9, in figure 5, are representing metamorphosed basic intrusions. Occurence of group 9 in the southeast corner of figure 5 correlates to portion of greenstone metavolcanic mafic unit. Groups 4 and 5 are present in areas corresponding to greenstone belt units and the Araxá Group. Groups 3 and *6* discriminate an area that should correlate with the Araxa Group. Group 1 dominates the area of figure 5 and shows no clear correlation to any specific lithologic unit.

When I applied the clustering method pn the samples for the whole set of gamma-ray spectrometric parameters, I obtained the results shown in figure 6. The main features found in figure 5 are present in a simpler picture defined by 5 groups. Group 1 dominates the map and again has no clear correlation to any specific lithology. Group 2 corresponds to areas of the geological map related to metamorphosed intrusions and mapped fault zones. Group 3 represents areas corresponding to metavolcanic mafic and ultramafic units and a portion of the Araxá Group. Groups 4 and 5 are representing portions of metavolcanic mafic units. A small occurrence of group 5 at the northern portion of figure 6 corresponds to intrusives.

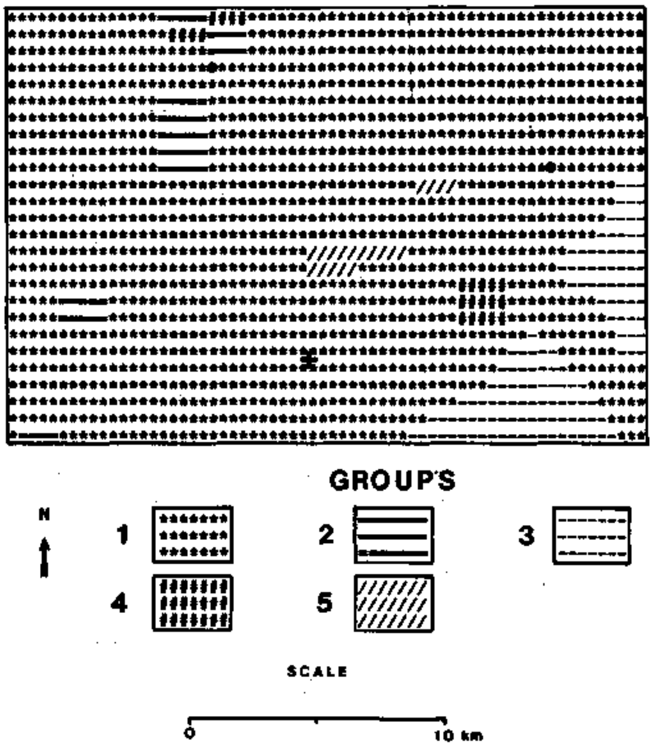

Figure 6 – Clustering results using U, Th, K, TC, U/Th, U/K, and Th/K as parameters in each sample. Location of Guarinos (W) and Pilar de Goiás (E) indicated by dots. Cross indicates point with 49° 40' longitude and 14° 50' latitude

Figura 6 – Resultados do agrupamento usando U, Th, K, TC, U/Th, U/K e Th/K como parâmetro em cada amostra. Localização de Guarinos (W) e Pilar de Goiás (E) indicada por pontos. A cruz indica o ponto de longitude 49° 40' e latitude 14° 50'

Results in figures 5 and 6 show groups that correlate to the north-northeast trending intrusives on the western portion of the geological map. Grouping was also produced where the metavolcanic units have a larger area expression. Grouping produced inside the region mapped as the Araxá Group has no correlation with features of the geological map.

Trying to impove the clustering results, I added to each of the three sets of gamma-ray spectrometric data the total magnetic field intensity values. The clustering produced by G-mode analysis on the new data sets did not show any significant changes. In figure 7, I show the results obtained using the gamma-ray ratios and the total magnetic field intensity values as variables in a sample. It can be readily observed that the result is very much like that of figures 5 and 6.

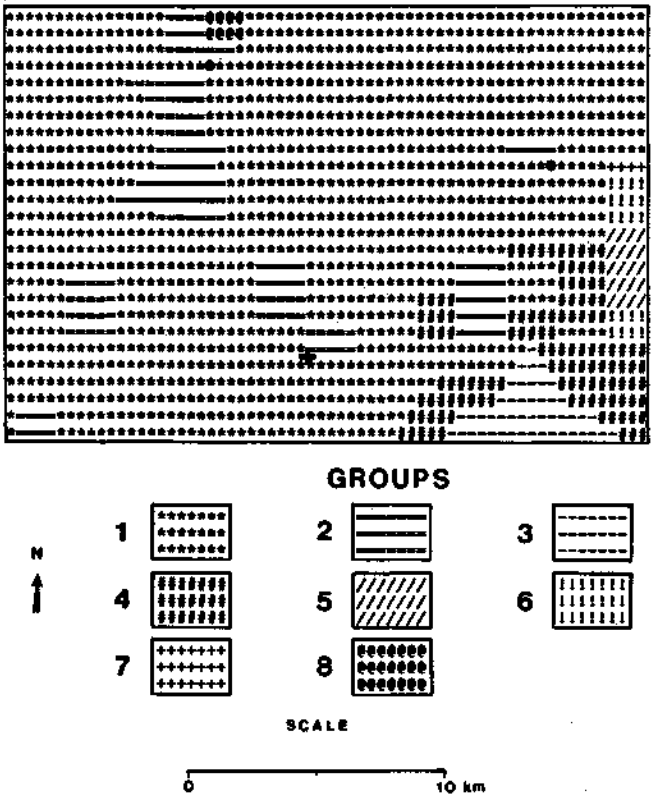

Figure 7 — Clustering results using gamma-ray spectrometric ratios (U/Th, U/K, and Th/K) and total intensity magnetic field as parameters in each sample. Location of Guarinos (W) and Pilar de Goiás (E) nidicated by dots. Cross indicates point with 49° 40′ longitude and 14° 50′ latitude

Figura 7 - Resultados do agrupamento usando as razoes gama-espectrométrícas (U/Th, U/K e Th/K) e intensidade total do camjpo magnético como parâmetro em cada amostra. Localização de Guarinos (W) e Pilar de Goiás (E) indicada por pontos. A cruz indica o ponto de longitude 49° 40' e latitude 14° 50'

From figure 4, the existence of three different magnetic patterns in the study area is very clear. By arbitrarily assigning the numbers 1, 2, and 3 to these patterns, I generated new data sets as explained earlier in this paper.

Figure 8 shows the G-mode clustering using, as variables, gamma-ray ratios and the magnetic pattern. Figure 9 shows the clustering results U, Th, K, TC, U/Th, U/K, Th/K, and magnetic pattern as variables. These two figures are very much alike and both have six groups describing the changes in the study area.

It is obvious that G-mode analysis incorporated the magnetic pattern into the statistical picture. Comparing the results of figures 8 and 9 with the mapped geology in figure2, a good agreement is easily seem between groups and lithologies.

As can be observed in figure 8, group 1 correlates with the Rio Caiamar and Rio Muquem granite-gneiss blocks. The Cedrolina granite-gneiss block, with a more complex lithology than the two previous blocks, corresponds to group

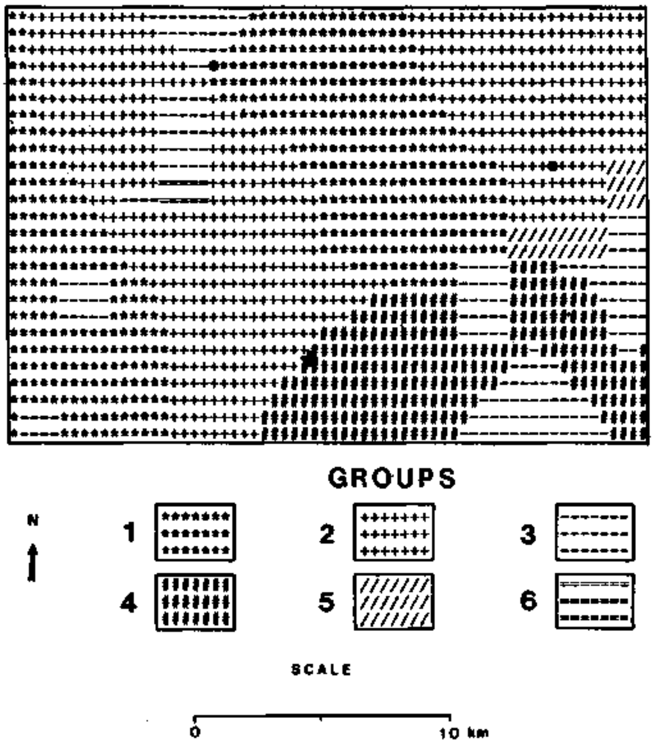

Figure 8 — Clustering results using gamma-ray spectrometric ratios (U/Th, U/K, and Th/K) and magnetic pattern as parameters in each sample. Location of Guarinos (W) and Pilar de Goiás (E) indicated by dots. Cross indicates point with 49° 40′ longitude and 14° 50′ latitude

Figura 8 - Resultados do agrupamento usando razões gama-espectrométrícas (U/Th, U/K e Th/K) e padrão magnético como parâmetro em cada amostre. Localização de Guarinos (W) e Pilar de Goiás (E) indicada por pontos. A cruz indica o ponto de longitude 49° 40' e latitude 14° 50'

2. Group 2 correlates, also, with greenstone belts trending north west-southeast and located east of Guarinos. Group 4 correlates well with the Araxa Group. Group 3 represents mafic lithologies corresponding to dikes, in the western portion of figure 8, and to greenstone meta volcanic units, in the eastern side. The presence of the group 3 in area already mapped as Araxa Group might suggest more mafic fades. Groups 4 and 5 have little presence and seem to be representing mafic lithologies.

Figure 9 reproduces the main characteristics observed in figure 8. However, the groups with smaller area representation in both figures have no common correspondence.

CONCLUSIONS G-mode clustering analysis applied on the gamma-ray spectrometric data presented results that, only in a few areas, correlate to the mapped geology. G-mode analysis using U, Th, K, and TC as variables produced clustering with no correspondence to the mapped geology .The inclusion of the total magnetic field values, as an additional variable in the cluster analysis, did not produce any significant improvement in the results.

The results obtained by the G-mode method, after the inclusion of the magnetic pattern as one of the variables, correlate well with the known geology. The main geologic units mapped in the area correlate with specific groups produced by the clustering procedure. The use of flight lines spaced 2 km did not allow identification of several features. The generally narrow metavolcanic units could not be

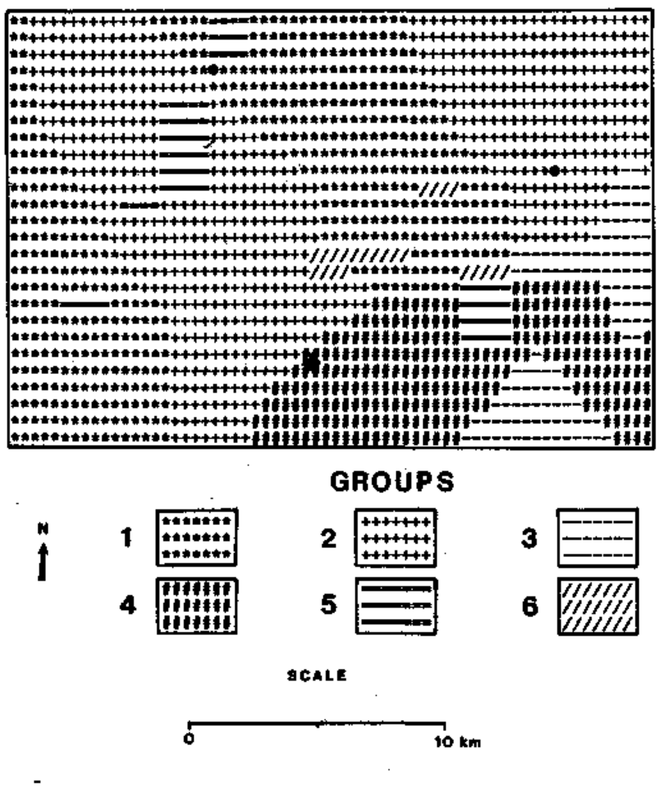

Figure 9 - Clustering results using U, Th, K, TC, U/Th, U/K, Th/K, and magnetic pattern as parameters in each sample. Location of Guarinos (W) and Pilar de Goiás (E) indicated by dots. Cross indicates point with 49º 40′ longitude and 14°50′ latitude

Figma 9 - Resultados do agrupamento usando U, Th, K, TC, U/Th, U/K, Th/K e padrão magnético como parâmetro em cada amostra. Localização de Guarinos (W) e Pilar de Goiás (E) indicada por pontos. A cruz indica o ponto de longitude 49° 40' e latitude 14° 50'

identified . However, this was possible in areas where they have larger area expression. The use of 1 km spaced flight lines would certainly produce better results.

The method was not able to separate the greenstone units from the granite-gneiss complex, the Cedrolina block, in the northeast portion of the study area. This suggests that the Cedrolina block could be considered as made of greenstone units rather than granite-gneiss complex rocks.

Some clusters produced by G-mode analysis have no clear correspondence with mapped geologic features. Examples are: the triangular feature in the southeast and clusters in the western portion of the statistical maps. These areas could be considered as targets for further field work.

A large portion of Brazil is covered with airborne magnetic and gamma-ray spectrometry. This data, acquired generally with 1 or 2 km flight line spacing, can be obtained of this data can certainly produce useful results, as suggested here.

As shown in this paper, G-mode analysis applied on the geophysical data was able to identify the main geologic units in the study area. This could be helpful in improving the geologic mapping of the area and setting targets for field work. Mineralization is known to occur associated with some of the identified units. Therefore, G-mode analysis could also be used as a tool for guiding mineral exploration in the region.

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