EVALUATING GEOSCAN AMSS MK-II FOR GOLD EXPLORATION IN THE FAZENDA MARIA PRETA DISTRICT, RIO ITAPICURU GREENSTONE BELT, BAHIA STATE, BRAZIL

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KEY-WORDS: Remote Sensing, Gold Exploration, Greenstone Belt.

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ABSTRACT

The Rio Itapicuru Greenstone Belt (RIGB), located in north-eastern Brazil, is an important gold producing region. It hosts two important mining districts, the Fazenda Brasileiro and the Fazenda Maria Preta, owned by Companhia Vale do Rio Doce (CVRD), plus a number of gold occurrences, all associated with hydrothermal alteration along shear zones. In 1992, Geoscan multispectral scanner data were acquired for mineral exploration purposes over more than 7,500 km^2 in this greenstone belt. Geoscan AMSS is a 24-band airborne scanner, with 5 meter spatial resolution. Standard image processing techniques, applied immediately after data acquisition, defined some spectral anomalies, particularly due to silicification and oxidation, which could be due either to hydrothermal alteration or to weathering processes. We have reprocessed the Geoscan data over a portion of the RIGB in order to define possible anomalies due to hydrothermal alteration minerals, using the feature-oriented principal component selection (FPCS) technique, modified for use with Geoscan data. Laboratory reflectance spectra of residual soils were acquired to establish superficial expression of hydrothermal minerals that occur in sub-surface and to guide image processing and interpretation. This led to the production of "mineral component" images, in which the spatial distribution of some minerals are shown. Results of the spectral analysis of soil samples showed that goethite may be used as a surface indicator of hydrothermal alteration and that it is not possible to differentiate the alteration zones from surrounding rocks based on the hydroxyl or carbonate spectral features.

RESUMO

O Greenstone Belt do Rio Itapicuru (RIGB), localizado no nordeste do Brasil, é uma importante região produtora de ouro no país. Ele contém dois importantes distritos mineiros, o da Fazenda Brasileiro e Fazenda Maria Preta, pertencentes à Companhia Vale do Rio Doce (CVRD), além de diversas outras ocorrências auríferas, todas elas associadas a processo de alteração hidrotermal ao longo de zonas de cisalhamento. Em 1992, imagens do sensor multiespectral Geoscan foram obtidas em mais de 7.500 km^2 do greenstone. O Geoscan AMSS Mk-II é um sensor aeroportado que cobre 24 bandas espectrais, com 5 metros de resolução espacial no caso deste levantamento. Técnicas padrão de processamento de imagens, aplicadas imediatamente após o levantamento, definiram uma série de anomalias espectrais, relacionadas a processos de silicificação e oxidação, que podem tanto ser devidos a processos de alteração

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hidrotermal quanto intempéricos. Esses dados foram reprocessados para uma porção do RIGB na tentativa de se definir possíveis anomalias espectrais devidas a minerais de alteração hidrotermal, utilizando a técnica denominada *feature-orientated principal component selection* (FPCS), modificada para uso com os dados Geoscan. Análises espectrais de laboratório foram realizadas em amostras de solos residuais e em rochas, no sentido de estabelecer a expressão superficial dos minerais de alteração hidrotermal que ocorrem em sub-superfície e orientar o processamento e a interpretação das imagens. Isso resultou na produção de imagens "componentes minerais", nas quais a distribuição espacial de alguns minerais de alteração é mostrada. Resultados da análise espectral de solos residuais mostraram que a goetita pode ser utilizada como um indicador superficial da presença de alteração hidrotermal e que não é possível diferenciar as zonas de alteração das rochas que as contém com base em feições espectrais de minerais contendo o ânion hidroxila ou carbonato.

INTRODUCTION

The use of remote sensing for mineral exploration, in particular for mapping hydrothermal alteration related to precious and base metals concentrations, has become operational in the last decade. Pioneer work by a number of authors, including Abrams et al. (1977, 1983), Rowan & Kahle (1982) and Podwysocki et al. (1983), demonstrated the potential of the 2.2 μm region of the electromagnetic spectrum for detecting hydroxyl-bearing minerals and carbonates usually associated with hydrothermal alteration processes. This was added to previous work demonstrating the usefulness of the visible/near infrared region of the spectrum for mapping Fe^{3+}-bearing minerals (Rowan et al., 1974, 1977; Goetz et al., 1975; Goetz & Rowan, 1981).

With the advent of Landsat Thematic Mapper in 1984, which covered both regions of the spectrum with six broad bands, an important tool for explorationists became available. This has led to the adoption of remote sensing by mining companies world-wide, making satellite imagery into another tool, usually to be used in conjunction with airborne geophysics and ground geochemistry in exploration projects, mainly in GIS environments.

However, most of these applications have so far been carried out in regions of arid and semi-arid climates, looking for hydrothermal alteration related to epithermal deposits. This has created a paradigm in terms of remote sensing applications to mineral exploration which has been successfully and repeatedly applied to similar areas world-wide. As new exploration frontiers for precious and base metals move into new regions of the world, unknown terrain must be addressed. These new areas may be located, for example, in areas of tropical to sub-tropical climates, with different geologic characteristics and usually with very little geologic information available. In this context, it has become essential to evaluate the use of remote sensing for mineral exploration under these new conditions, in order to determine to which extent these data can offer positive answers to exploration needs.

One of the areas in the world to which exploration activities are currently moving into is Brazil. This is particularly true in the case of gold, since the country is the 7th biggest producer in the world, with an output of 70 m. tons. in 1994, reserves of 760 m. tons. and a good potential for new world-class deposits. Remote sensing, together with other exploration techniques, is likely to play a key role in gold exploration in Brazil, due to the vast extension of exploration grounds and the lack of sound base and geologic maps. It is therefore important to analyse the potential of remote sensing data for different applications in mineral exploration in Brazil, including hydrothermal alteration mapping.

Landsat Thematic Mapper data have been used for mapping hydrothermal alteration in Brazil. Results presented by Crósta & Rabêlo (1993), Ferreira (1993), Hernandes (1994), Hernandes & Crósta (1996) have shown that it is possible to identify areas of hydrothermal alteration related to gold mineralization in Brazil through Landsat TM. All the areas studied by these authors have medium to low-density vegetation cover of the savannah type (*cerrado*), which is typical of central Brazil and would allow ground spectral information to be collected by remote sensors, particularly during dry season. However, these authors pointed out problems related to the very limited spectral resolution of the sensor, which did not allow the separation of OH-bearing minerals formed by alteration from those formed by regional metamorphism in the surrounding areas. Alteration minerals may also be masked by weathering and laterization processes which are widely present in tropical and sub-tropical climates.

In 1992, Docegeo (Rio Doce Geologia e Mineração) decided to acquire higher spectral resolution remote sensing data for some areas located in central and north-eastern Brazil. The selected sensor was the Geoscan airborne multispectral scanner (AMSS), providing coverage in 24 spectral bands in the visible-near infrared (VNIR), shortwave infrared (SWIR) and thermal infrared (TIR). One of the areas selected by Docegeo for this survey was the Rio Itapicuru Greenstone Belt (RIGB), in Bahia State. Image processing techniques, applied immediately after data acquisition by the contractor (Prospec/ Geoscan Pty.), comprised mostly band differencing and ratioing. This allowed for a number of spectral anomalies to be found, mainly related to silicification (quartz veins) and oxidation (gossans). No significant results were found in terms of spectral anomalies related to clay minerals and/or to carbonates, described by many authors as related to the gold mineralizations in this area.

We have reprocessed these data over the central sector of the RIGB, known as Maria Preta District, in order to investigate the existence of "clay" (general term for O-H-bearing minerals formed by hydrothermal alteration) and carbonate spectral anomalies, using the technique called Feature-Oriented Principal Component Selection (FPCS) (Crósta & Moore, 1989), adapted for Geoscan data. The objective was to identify spectral signatures related to alteration minerals and to establish a methodology to process the entire Geoscan dataset for this region (covering a total of more than 7,500 km^2). In order to define spectral differences between residual soils of altered and non-altered areas and to establish spectral signatures of alteration minerals, laboratory reflectance spectra of residual soils were acquired for several exploration targets in the Fazenda Maria Preta District.

GEOLOGY AND GOLD MINERALIZATION OF THE RIO ITAPICURU GREENSTONE BELT

The metassedimentary rocks at Rio Itapicuru were first recognised as a greenstone belt by Mascarenhas (1973) and Kishida (1979) and comprise a north-south trending sequence of mafic, ultramafic and felsic rocks, intruded by granitic domes dated of Lower Proterozoic age, covering an area of approximately 7,500 km^2. This sequence occurs along the middle course of the Itapicuru River, in Bahia State. The basement consists of Archaean gneissic, migmatitic and granulitic rocks of the São Francisco Craton. The N-S structural trend changes into E-W in the southern portion of the belt, which contains most of the known gold reserves. Figure 1 shows a generalised geologic map of the RIGB and its location.

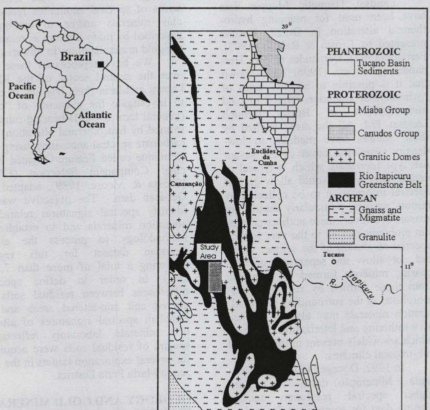

Figure 1 - Generalized geological map of the Rio Itapicuru Greenstone

According to Kishida (1979) the volcano-sedimentary sequence comprises three units, from bottom to top: the Mafic Volcanic Domain (tholeiitic basalt, basaltic pillow lava, carbonaceous chert, tuff, banded iron formation, graphitic slate with pyrite and breccia), the Felsic Volcanic Domain (andesitic tuff, dacite, chert, andesite, serpentinized ultramafic and quartz diorite) and the Sedimentary Domain (siltstone and slate). The sequence is intruded by syn-tectonic (foliated) granites, post-tectonic granitoids and gabroic sills.

There are two major mining districts within the RIGB: the Fazenda Brasileiro in the southern sector, and the Fazenda Maria Preta in the central sector. The two biggest mines in these districts are owned by Companhia Vale do Rio Doce (CVRD).

The Fazenda Brasileiro District is located in the southern portion of the RIGB, known as the Weber Belt, and comprises several discontinuous ore bodies (Fazenda Brasileiro, Canto I and II, Incó, Gente, Abóbora and Pau-a-Pique) distributed along 10 km in a E-W ductile-brittle shear zone. The Fazenda Brasileiro Unit, which hosts the mineralization, comprises the following lithologies: carbonaceous schist, quartz-magnetite-chlorite schist (also called "magnetic schist"), containing the mineralization, and rocks of gabroic composition placed in between the magnetic schist (Kishida et al., 1991). The mineralization is controlled by dextral ductile-brittle shearing and by the magnetic-schist, which provided the necessary chemical environment (Reinhardt & Davison, 1990). There are two types of ore: a stratabound-like ore comprising disseminated gold with sulphides (arsenopyrite, pyrite, pyrrotite, chalcopyrite and galena) and oxides (magnetite and ilmenite), formed along a silicified shear zone in the magnetic-schist, and disseminated native gold in quartz veins and stockworks, distributed without stratigraphic control. The hydrothermal alteration is characterised by an increase in Na, CO_2, As and S, producing albite, carbonate and sulphide (Kishida et al., 1991). The reserves of Fazenda Brasileiro are 140 metric tons of Au.

The Fazenda Maria Preta District comprises two trends: Antas-Maria Preta (orebodies Antas I, II and III, and C1N) and Mansinha (orebody M11) (Rocha Neto, 1994). Mineralization is associated with two ductile-brittle shear trends, both N-S. The ore is hosted by carbonaceous phyllonites, in quartz-albite-ankerite veins and veinlets. Gold occurs as inclusions in arsenopyrite and pyrite and also as free gold in hydrothermal chlorite, micas and quartz veins. Hydrothermal alteration is widespread in the entire Maria Preta District, being more intense near the ore bodies, and comprises an assemblage of quartz, sericite, carbonate, sulphide and epidote. Gold reserves in the Fazenda Maria Preta District are approximately 6 metric tons.

SENSOR AND TERRAIN CHARACTERISTICS

Remote sensing data for the RIGSB were acquired by Geoscan Airborne Multispectral Scanner (AMSS) MK-II, in 24 spectral bands, with a 5 meter spatial resolution (flight altitude of 2,386 meters). The survey was carried out in September 1992, using a Cessna 404 Titan aircraft. The flight direction was North-South, parallel to the main structural trend of the northern portion of the RIGSB. Table 1 shows the spectral characteristics of the sensor. Bands 1 to 10 cover the visible and near-infrared (VNIR) portion of the electromagnetic spectrum, from 0.48 to 0.96 µm, bands 11 to 18 the shortwave infrared (SWIR), from 2.00 to 2.39 µm, and bands 19 to 24 the thermal infrared (TIR), from 8.11 to 11.81 µm.

The standard method of radiometric correction used in Geoscan data is to set the values of gains and offsets individually for each spectral band, through an initial test flight over the area. The offset of each band is set to a value of 127 and an optimal gain is established using an 8-bit dynamic

Table 1 - Geoscan AMSS MK-II band specifications (band centers and band widths are given in nanometers).

Band		Center Wavelenght	Bandwidth
1		522	42
2		583	67
3	V	645	71
4	N	693	24
5	I	717	24
6	R	740	23
7		830	22
8		873	22
9		915	21
10		955	20
11		2,044	44
12		2,088	44
13		2,136	44
14	S	2,176	44
15	W	2,220	44
16	I	2,264	44
17	R	2,308	44
18		2,352	44
19		8,640	530
20	T	9,170	530
21	I	9,700	530
22	R	10,220	533
23		10,750	533
24		11,280	533

range (Lyon & Honey, 1989; Lockett et al., 1993; Agar, 1994). Due to this adjustment, no further radiometric correction is necessary. Although this procedure makes it difficult to convert these data from DN values to radiance or reflectance, since the information of the original dynamic range is not preserved, Lyon & Honey (1989) demonstrated that it is possible to spectrally analyze Geoscan data in relation to spectral library data.

Geometric corrections are applied, to minimise major distortions towards both ends of the scanning lines (tan θ); these corrections are described by Locket et al. (1992). However, due to the low flight altitude in relation to the relatively large swath width, and also to the inherent characteristics of the sensor optical system, remaining geometric distortions are still considerable, making it difficult to achieve low positional errors (RMS), when applying a geometric correction based on ground control points.

Analysis of the data acquired for the RIGB revealed severe noise problems, affecting particularly the SWIR and the TIR bands. However, this problem apparently did not affect all flight lines in the same way or intensity. For some lines, it was found that the SWIR bands (11 to 18) were almost unusable, whereas for others flight lines the same bands had less noise. This problem was associated with the presence of clouds in the area, since the noise appeared in the lines scanned after a cloud was present; it therefore appears that the cloud strongly affected the gain of the scanner. The TIR bands were, without exception, noisy in all flight lines examined, particularly bands 21, 23 and 24. These noise problems affected spectral ranges of great importance for detecting the types of hydrothermal alteration present in the study area (hydroxyl-bearing minerals and carbonates in the SWIR and silica in the TIR), and therefore must have also affected the results presented in this paper.

The characteristics of the terrain in the RIGSB include scarce vegetation cover of the *caatinga* (semi-deciduous thorn scrub, sometimes with cactus and palmtrees, found in areas where the climate is sub-humid to arid in north-eastern Brazil), which favours the use of remote sensing. However, the original vegetations is often degraded in the study area, sometimes replaced by sisal crops (an evergreen shrub, with large and long leaves). The presence of these crops, in different growing stages (shown as square patterns on the images), obscured somewhat the spectral response from soils and rocks, but did not prevent the use of remote sensing. Rocks are heavily weathered near the surface, with a residual soil cover several meters thick and few rock outcrops appearing mainly in silicified zones and areas of granitic lithologies. The metavolcanics are characterised at the surface by intensely oxidised (red) soils, with a typical lateritic profile.

DATA PROCESSING

Geoscan AMSS data for the RIGB were initially processed by the contractor using band differencing and ratioing. This allowed the interpretation of a number of spectral anomalies, almost all related to oxidation and the formation of hematite, goethite and limonite, as possible products of weathering of sulphides (Fig. 2). These techniques did not reveal significant anomalies for other minerals, despite the fact that sericite and carbonates, minerals potentially identifiable by Geoscan AMSS bands due to the O-H and the CO_3 absorption features in the 2.0 to 2.5 μm range, have been described in association with hydrothermal alteration in the Fazenda Maria Preta district.

It was therefore decided to investigate the possible existence of spectral anomalies due to these minerals, using the technique called Feature-Orientated Principal Component Analysis (FPCS) (Crósta & Moore, 1989; Loughlin, 1991; Crósta & Rabêlo, 1993). FPCS offers advantages over simple band ratioing or differencing, since it uses at least four original bands to investigate the presence of each mineral or mineral group. This allows to include a greater spectral range into the analysis and, therefore, more diagnostic features for each mineral.

FPCS was originally designed to process Landsat TM bands and has been adapted for Geoscan AMSS. This adaptation took advantage of the higher spectral resolution of Geoscan AMSS over TM, which allows a number of specific minerals to be mapped, instead of only mineral assemblages as with TM. The adaptation consisted of selecting specific band sets, according to the minerals to be tested and their most important diagnostic features. The band sets were defined based upon the spectra obtained from the JPL and USGS spectral libraries (Grove et al., 1992; Clark et al., 1993). In order to define the position of these features for the alteration minerals found at Fazenda Maria Preta, residual soils samples were spectrally analysed, as described in the next section.

Table 2 shows the band sets used for each mineral, or mineral group in the cases which Geoscan could not resolve among them. It also shows band sets for mapping iron minerals and silica. Each set of four bands was selected based upon the spectral characteristics of the mineral(s) at the specific wavelength range represented by the bands. Typically, two of the selected bands represent wavelength ranges in which the minerals have characteristic absorption features (represented in these bands by pixels with low DN values) and the other two represent ranges in which they show high spectral response (high DN values). For example, the band set selected for hematite include Geoscan bands 1 and 7, corresponding respectively to wavelength ranges of 501-543 nm and 819-841 nm, in which this mineral absorbs the energy, and

Figure 2 – Color composite of band differences (B2-B1), (B3-B2) and (B6-B8) in RGB.

Table 2 - Geoscan band sets for the minerals of interest, used as an input to principal component analysis.

Minerals	Hematite	Limonite	Goethite	Chlorite/ Calcite/ Epidote	Sericite/ Kaolinite	Silica
	B1	B1	B1	B1	B1	B1
Geoscan	B6	B6	B6	B8	B8	B10
Bands	B7	B8	B9	B12	B11	B20
	B12	B12	B12	B18	B15	B23

bands 6 and 12, corresponding respectively to 730-752 nm and 2,022-2,066, in which hematite strongly reflects electromagnetic energy. All the other band sets are selected in the same way, including the one for silica. In this case, it is possible to use bands in the visible (B1) and near-infrared (B10), together with thermal bands (B20 and B23), because they are all converted to the same dynamic range of 0-255, despite the fact that they represent energy of different nature. Therefore, pixels containing silica will be represented by low DN values in Geoscan bands 1 and 20 and by high DN values in bands 10 and 23.

After selecting specific band sets for minerals of interest, principal component analysis (PCA) was applied to each of these sets and interpreted in the same way as with TM data, as described by Loughlin (1991) and Crósta & Rabêlo (1992). According to these authors, "mineral component" images are defined through the analysis of eigenvector coefficients and the identification of the principal component image containing the desired spectral information. Tables 3A through 3F show the eigenvector coefficients (expressed in percentage), obtained through PCA of band sets shown in Table 2. The PC image which shows the highest contrast between the pair of bands with diagnostic absorption and reflection features for the specific mineral is selected as the "mineral component" image for that mineral. In Table 3A (hematite) for example, the "component" containing most of the spectral information due to this mineral is PC4, because it has high values (in module) for band 6 (in which ferric iron strongly reflects energy) and band 7 (in which it strongly absorbs), but with opposite signs, thus representing the spectral contrast for this mineral. Because the eigenvector coefficient is negative for band 6 and positive for band 7, pixels containing iron oxide will be displayed in dark tones (low DNs). This result can be visually enhanced by inverting PC4, thus converting these dark pixels into bright ones. A similar analysis is performed in eigenvector coefficients of all band sets (tables 3B through 3F), thus defining the other "mineral components".

Figure 3 shows "mineral components" sericite, chlorite and goethite for the Fazenda Maria Preta district. Bright pixels indicate the presence of the respective mineral in each "component". Bright areas in the upper left side of Figure 3 correspond to the pits of the Fazenda Maria Preta district, showing a high spectral response for goethite, high-medium for sericite and low for chlorite. A similar decrease in chlorite in the alteration zone compared to the host rock was observed by Kishida et al. (1991) in the Fazenda Brasileiro district, together with an increase in albite, carbonate and sulphides. The increase in goethite and sericite, shown in Figure 3a and 3c for the mine pits, could be the

Table 3 - Eigenvectors coefficients (in percentage) obtained through principal component analysis for Geoscan band sets shown in Table 2.

	PC1	**PC2**	**PC3**	**PC4**
B1	13.46	36.22	49.49	6.51
B6	33.24	-6.29	0.68	**-51.32**
B7	41.01	-18.54	-2.67	**38.30**
B12	12.39	38.95	-47.16	3.87

(A - Hematite Band Set)

	PC1	**PC2**	**PC3**	**PC4**
B1	17.17	31.95	49.15	6.57
B6	32.86	-11.96	0.82	**-48.23**
B8	33.70	-21.32	-3.19	**42.05**
B12	16.27	34.77	-46.84	3.15

(B - Limonite Band Set)

	PC1	**PC2**	**PC3**	**PC4**
B1	16.60	32.62	46.83	8.23
B6	32.29	-11.55	3.33	**-49.71**
B9	35.21	-20.70	-4.70	**41.54**
B12	15.90	35.13	-45.14	0.52

(C - Goethite Band Set)

	PC1	**PC2**	**PC3**	**PC4**
B1	27.05	1.30	53.60	14.58
B8	7.99	-80.23	-4.63	0.32
B12	30.40	7.24	-7.39	**-51.39**
B18	34.56	11.23	-34.38	**33.71**

(D - Chlorite/Calcite/Epidote Band Set)

	PC1	**PC2**	**PC3**	**PC4**
B1	25.12	-3.07	-55.28	3.52
B8	5.35	-82.38	5.53	1.22
B11	30.92	5.74	20.06	**51.73**
B15	38.61	8.81	19.13	**-43.53**

(E - Sericite/Kaolinite Band Set)

	PC1	**PC2**	**PC3**	**PC4**
B1	13.13	22.31	-60.13	2.82
B10	11.73	53.45	27.89	0.41
B20	35.02	-10.28	3.88	**-52.23**
B23	40.12	-13.96	8.10	**44.54**

(F - Silica Band Set)

result of alteration and weathering of sulphides and albite. Despite strong noise problems in the TIR bands, a "silica" component has been generated, which also shows spectral anomalies.

Figure 4 presents color composite images of some the "mineral components". Figure 4a is a composite of the goethite, sericite and silica components in RGB. Figure 4b shows the components goethite, goethite+sericite and sericite in RGB (using the same color scheme as in Loughlin, op. cit.) and Figure 4c depicts the same image as 4b, with the locations of the identified occurrences of spectral anomalies and the

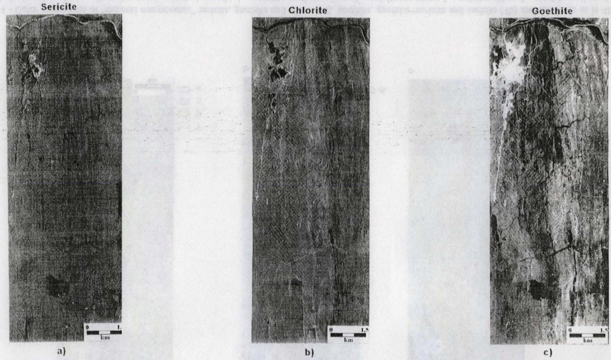

Figure 3 - “Mineral Components” for sericite (3a), chlorite (3b) and goethite (3c) produced by the application of FPCS to Geoscan band sets described in Table 2. Bright pixels indicate high concentration of the respective mineral.

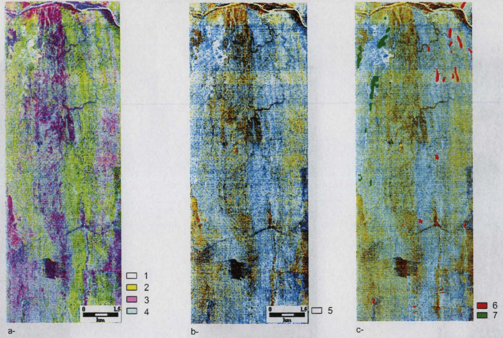

Figure 4 - Color composites of "mineral components" sericite, goethite and silica (4a), goethite, goethite+sericite and sericite (4b) and the same as in 4b, but with the location of mine pits and anomalies (4c). Legends: 1 - sericite+goethite+silica; 2 - sericite+goethite; 3 - sericite+silica; 4 - goethite+silica; 5 - Anomalies; 6 - Anomalies; 7 - Mine pits.

mine pits of the Fazenda Maria Preta district overlaid on top.

It must be emphasised the noise problems in the data (SWIR and TIR bands) had a strong negative effect over the results. This is because principal components analysis, the statistical technique used by FPCS, concentrates noise in the lower order components. These are the same components that contain spectral information from minerals, which is therefore mixed with the noise.

SPECTRAL ANALYSIS OF RESIDUAL SOILS

In order to guide the processing and interpretation of multispectral imagery acquired by the Geoscan in the Fazenda Maria Preta district, where little or no outcrops of hydrothermally altered rocks are found on the surface, it is necessary to establish some relationship between the mineralogy of surficial soils and that of altered rocks. For any sensor to be able to detect hydrothermal alteration, it is necessary that at least some mineral indicators show up at the surface, in this case in the residual soils.

The processes that form residual soils in tropical and sub-tropical climates are a result of mineralogical changes, which may cause primary and secondary (or weathering) minerals to mix together. These processes are not yet fully understood in terms of mineral transformations. Tardy (1993) reports about a controversy regarding the origin of one of the commonly assumed indicators of hydrothermal alteration, sericite (a name used to designate microcrystalline white micas, including muscovite, illite and hydromuscovite). For some authors, sericite found in tropical environments is formed mostly by weathering of plagioclases (albite-anortite), whereas others support the idea of sericite as a product of hydrothermal alteration of these minerals. According to these ideas, sericite may be found in soils associated with hydrothermal alteration, or as a result of weathering of feldspar-rich rocks or even associated with sericite-bearing metamorphic rocks.

Fe^{3+} oxides and hydroxides are also important indicators of mineral deposits related to hydrothermal alteration, formed as a weathering product of sulphides. In sub-tropical climates these oxides and hydroxides may form a complex mixture called limonite, comprising variable proportions of hematite and goethite. High concentrations of limonite, together with amorphous iron oxide, may occur in association with some types of mineral deposits but it also occurs as ferruginous lateritic crusts, typical of tropical environments, bearing no relationship with mineral deposits. Although not enough conclusive evidence is available, some authors have described a greater proportion of goethite over hematite in gossans derived from sulphides in mineral deposits (Fraser et al., 1985, 1986; Raines et al., 1985; Hernandes, 1994). On the other hand, ferruginous lateritic processes, common in tropical and sub-tropical climates, have an opposite tendency, forming oxidised material with a significant greater proportion of hematite over goethite. Raines et al. (1985) concluded that true gossans could be differentiated from ferruginous laterites based on the greater concentration of goethite in the former. This conclusion could therefore serve as a basis to map gossans using remotely sensed data, since both minerals have distinctive diagnostic spectral features in the visible-near infrared portion of the spectrum. However, Fraser et al. (1986) found at least one example of a true gossan in which goethite was not prevalent over hematite, in the Lady Loretta deposit, Queensland, Australia.

Studies carried out in Brazil showed that residual soils derived from hydrothermally altered rocks show spectral features of hydrothermal minerals (Crósta & Rabêlo, 1993; Ferreira, 1993; Hernandes, 1994; Hernandes & Crósta, 1995; Crósta et al., 1996).

Although further research still needs to be done to better define spectral characteristics of residual soils derived from hydrothermal altered rocks in areas of different climates, these parameters are currently being successfully used in mineral exploration activities world-wide.

Considering these aspects, spectral analysis of residual soils and rocks associated with hydrothermally altered areas and its host rocks in the Fazenda Maria Preta district was done. The objectives of the analysis were: (i) to investigate the possible relationship between the occurrence of hydrothermal alteration in sub-surface and the corresponding residual soils; (ii) to establish the spectral characteristics of these soils and (iii) to determine whether a spectral "contrast" exists between these soils and those of surrounding areas, corresponding to the host or "non-altered" rocks, that could be used to guide band selection and image processing.

A Beckman UV-5240 spectrophotometer and an GER IRIS Mk-IV were used to spectrally analyse the soils. The first instrument is equipped with an integrating sphere for the measurements, while the measurements made with the GER IRIS instrument are dependent of the geometry between the sample, an energy source and the sensor head. The geometry used is the same described by Formaggio et al. (1996) for analyzing soil samples. It should be pointed out that the Beckman had an instrument problem in the 400 to 550 nm range, which affected the results at these wavelengths. The IRIS instrument showed also an overall high noise level, affecting all the measured spectra. X-ray diffraction analysis of all the samples was also carried out, in order to confirm some of the minerals detected by reflectance spectrometry.

Most of the spectral absorption features showing up in the spectra are due to the presence of Fe^{3+} and OH^{-}. The discussion that follows will therefore concentrate on the minerals bearing these ions.

Figure 5 (a, b, c) and 6 (a, b) show the spectral curves of samples collected along several transects cutting across the linear alteration zones. They were collected over three different portions of the Fazenda Maria Preta gold deposit, respectively named Antas III/Corpo I, Antas III/Corpo III and Antas II/Corpo I. For all transects at least one residual soil sample from each of the following was collected: hydrothermally altered rock, non-altered host-rock and ore (marked with an asterisk). The samples of nonaltered host rocks were collected at distances ranging from tens to a few hundred meters from the center of the ateration zone.

Despite the problems with the Beckman, all the samples analysed showed a generalised absorption feature in the visible portion of the spectrum, with the reflectance increasing considerably towards the near infrared (400 to 800 nm), as can be seen in figures 5 and 6. This feature is very typical of the presence of Fe^{3+} and is caused by an electronic charge transfer in this ion. A second important spectral feature is the remarkable absorption that occurs between 850 and 950 nm in all samples except AN-00 (Fig. 6a). This feature is also typical of the presence of Fe^{3+}, caused by a crystal field effect and used to differentiate hematite from goethite and from limonite.

In the spectral curves for samples AN-07 and AN-08 (Fig. 6a) this feature is more subtle and broad, occurring

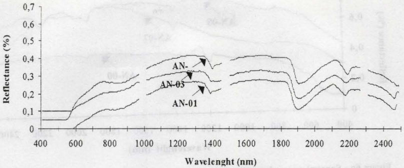

Figure 5a - Spectral curves for soil samples from Antas III/Corpo 1 (Beckman instrument).

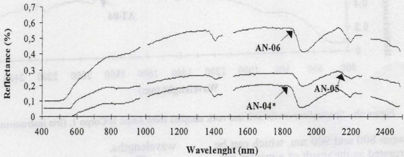

Figure 5b - Spectral curves for soil samples from Antas III/Corpo 3 (Beckman instrument).

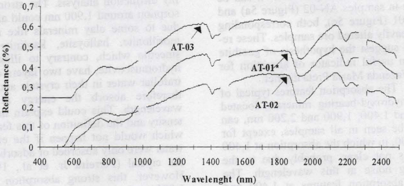

Figure 5c - Spectral curves for soil samples from Antas II/Corpo 1. (Beckman instrument).

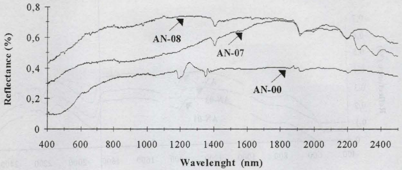

Figure 6a - Spectral curves for soil and rock samples from Antas III/Corpo 1. (Iris instrument).

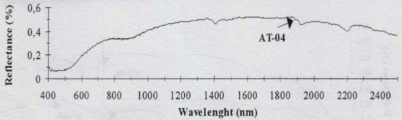

Figure 6b - Spectral curves for soil and rock samples from Antas II/Corpo 1. (Iris instrument).

between 800 and 900 nm, which can be interpreted as the result of a greater proportion of amorphous iron material (limonite). A secondary crystal field absorption near 650 nm is diagnostic of goethite and, although subtle, it can be seen in samples AN-02 (Figure 5a) and AT-01 (Figure 5c), both corresponding to heavily altered ore samples. These results suggest the hypothesis of goethite as an useful indicator of alteration for the Fazenda Maria Preta district.

The absorption features typical of the hydroxyl-bearing minerals, located around 1,400, 1,900 and 2,200 nm, can also be seen in all samples, except for AN-00, in which the absorption at 1,400 nm is not clear, probably due to the strong noise at this wavelength. The OH^- absorption features at 1,400 and 1,900 nm should be analysed with some care, since water absorbs at the same wavelengths.

The features seen around 1,400 and 2,200 nm in all samples are probably due to illite, maybe to kaolinite and smectite. This is also confirmed by X-ray diffraction analysis. The strong absorption around 1,900 nm could also be due to some clay minerals like montmorillonite, halloysite, kaolinite and smectite which, contrary to illite and hydromuscovite, have two layers of intrafoliar water in their crystals and will therefore absorb the energy at this wavelength. This could explain the intensity and the definition of this feature, which would not happen if the excess water were only absorbed or adsorbed in the crystal (Ferreira Jr. et al., 1993). However, this strong absorption near 1,900 nm is not seen in previously dried samples analysed using the IRIS instrument, except for sample AN-00, which shows an incipient absorption feature at 1,900 nm.

The single absorption feature near 2,200 nm shows a slight shift between 2,180 and 2,210 nm, independent of the location of the samples in regard to the alteration. This feature can be assigned to illite, which usually shows a shift between 2,190 and 2,210 according to the level of crystallinity of the specific sample (Clark et al., 1993). A double absorption feature (doublet) around 2,200 nm, diagnostic of minerals of the kaolinite group (kaolinite, halloysite and dickite), is not observed in any of the samples analysed. As X-ray diffraction analysis showed the presence of kaolinite in some samples, this may be due to the strength of the single feature of illite, which may be hiding the kaolinite feature and possibly indicating that the amount of illite is much greater than the amount of kaolinite.

The overall spectral results obtained for all samples at Fazenda Maria Preta district at the 2,000-2,300 nm range are similar. They show that it is not possible to achieve a clear distinction between hydrothermally altered and less-altered to non-altered host-rocks in this range of the electromagnetic spectrum. This poses a problem, since all the hydroxyl-bearing and carbonate minerals related to alteration show diagnostic features in this region. This similarity may indicate that: (i) the alteration at Fazenda Maria Preta is much more laterally widespread than previously thought; or, more probably, (ii) the feature around 2,200 nm is mainly related to clay (O-H-bearing) minerals produced by weathering processes, without a direct relationship with the hydrothermal alteration that affect the bedrock.

CONCLUSIONS

Geoscan data has been shown to be effective for mapping hydrothermal alteration in the RIGB. The feature-orientated principal component selection technique, selected for processing the data, was able to deal with the 24 band spectral dataset very efficiently, enabling to produce mineral component maps which show the spatial distribution of some minerals with diagnostic spectral features in the portion of the electromagnetic spectrum covered by the sensor. Positive results in terms of mineral mapping were obtained, despite the fair amount of vegetation cover and the presence of a relatively thick weathering profile over the bedrock. However, more research needs to be done in regard to the origin of some of the minerals identified on the imagery, in order to determine whether they were formed by hydrothermal processes or by weathering. Also, further research is needed regarding the mineralogy of soils formed by weathering of hydrothermally altered rocks in this heavily laterized region, in order to make proper use of medium to high-resolution remote sensing data in non-arid environments. Agricultural activity in the study area, particularly sisal crops, did not prevent mineral features to be identified, although these are clearer in areas of exposed soils.

Spectral analysis showed that some samples collected at mineralised sites display a subtle absorption feature at 650 nm which, combined with the main Fe^{3+} main feature around 900nm, suggests the presence of goethite. Thus, goethite appears to be an indicator of the presence of hydrothermal alteration in subsurface at Fazenda Maria Preta, corroborating similar results obtained elsewhere in Brazil and other areas of the world. In the 2,200 nm region almost all samples show a similar absorption feature, interpreted as mostly due to illite, regardless of their distance from the main alteration zone. Spectral features that could be assigned to other hydroxyl-bearing minerals (such as kaolinite, montmorillonite) and carbonates were not found in the spectra naalysed. Weathering is the likely cause of this absence in the surface soils and rocks, since it is possibly transforming pre-existing hydroxyl-bearing minerals into illite and leaching the carbonates. For this reason, weathering may be considered a major obstacle for alteration mapping in the RIGB using multispectral remotely sensed imagery such as Geoscan.

These results show that a more comprehensive research on the spectral characteristics of hydrothermally altered rocks and related soils need to be done for tropical and sub-tropical environments commonly found in Brazil, in order to guide future use of high spectral resolution remote sensing. Without such research, the cost-benefit relationship in using airborne or spaceborne sensors of this kind will not be established and this may not encourage the operational use of this technology for mineral exploration purposes in these environments. This research will also be of great importance in preparation for the advent of hyperspectral sensors on-board satellites, which are likely to become operational in the near-future (Taranik & Crósta, 1996).

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