

DIGITAL PROCESSING AND GEOLOGICAL INTERPRETATION OF TM-LANDSAT IMAGES OF THE AREA EAST OF THE CAMAQUÃ MINE IN RIO GRANDE DO SUL STATE, SOUTHERN BRAZIL

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ABSTRACT

The Camaquã basin was formed during the closing stages of the accretion of Gondwanaland. The sediments were deposited over mylonites of the Porongos Complex. Two sequences of silici-clastic sediments are present, the lower Santa Bárbara Formation and the upper Guaritas Formation, which is intruded by the Rodeio Velho calc-alkaline rocks. Relief is strongly controlled by lithology and structure, with an overall rectilinear drainage pattern. Vegetation is formed by grasses together with subordinate bushes and trees which are either scattered over the countryside or form small woods and dominates the spectral response. Soil cover is thin and rock outcrops are common, although subordinate. Based on field data, statistical parameters for atmosphere-corrected bands 2, 3, 4, 5 and 7 were set up, and served as a base for the digital processing. Greater lithological contrasts were obtained by Principal Component Analysis (PCA) through comparison of results of statistical analysis of the transformed parameters and of the original bands. A preliminary analysis of the images thus obtained led to the identification of different spectral patterns. The component PC1 reflects textural patterns related to the relief and the different albedos. In PC2, the spectral response of trees highlighted the Porongos Complex and the Rodeio Velho andesites, while grasses accentuated areas of fine-grained sandstones of the Santa Bárbara and Guaritas Formations. In PC4, the sandstones and conglomerates of the two sequences, together with quartzite hills of the basement complex, are prominent.

RESUMO

A Bacia do Camaquã originou-se nos estágios finais da acreção do Supercontinente Gondwana. Os sedimentos formados depositaram-se sobre o embasamento do Complexo Porongos. Destacam-se duas seqüências sedimentares siliciclásticas, na base, a Formação Santa Bárbara, e a superior, Formação Guaritas, na qual ocorrem as intrusões cálcio-alcálicas Rodeio Velho. A seqüência superior (Formação Guaritas) compõe-se de duas unidades, na porção basal, de arenitos eólicos, e arenitos e conglomerados flúvio-deltaicos na parte superior. Os diversos corpos intrusivos cálcio-alcálicos Rodeio Velho (rochas andesi-basálticas), mais jovens, instalaram-se, preferencialmente, na interface entre essas

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duas unidades. O relevo mostra-se fortemente influenciado pela litologia e pelas estruturas geológicas, com padrão geral dendrítico de drenagem. A vegetação domina a resposta espectral, compondo-se de gramíneas com algumas árvores e arbustos dispersos pelos campos ou em pequenos grupos. A cobertura do solo é bem delgada a ausente, propiciando uma exposição subordinada das litofácies. De acordo com dados reunidos em trabalhos de campo, foram coletados parâmetros estatísticos nas bandas originais 2, 3, 4, 5 e 7 sem qualquer tratamento prévio, os quais serviram de base para o processamento digital das imagens. Os maiores realces de litologia foram obtidos através da Análise por Principais Componentes (APC) comparando-se os resultados com os parâmetros estatísticos transformados e das bandas originais. A análise preliminar das imagens obtidas permitiu a identificação de padrões espectrais diferentes para os vários litotipos. A componente PC1 refletiu padrões texturais relacionados com o relevo e diferenças de albedo da vegetação e de rocha exposta. Na PC2 ficou evidenciada a resposta espectral da vegetação arbórea, realçando-se o embasamento e os andesitos Rodeio Velho, e de gramíneas em áreas de exposição de arenitos finos da Formação Santa Bárbara e da Formação Guaritas Inferior. Na PC4 evidenciou-se os arenitos e conglomerados das duas seqüências, além das cristas quartzíticas do embasamento, ou seja, rocha exposta.

INTRODUCTION

The Camaquã basin is situated in the State of Rio Grande do Sul, the southernmost state of Brazil. The state is an area of great geological interest, both as a traditional copper-producer and as a region of very varied and well-exposed geological features (Fig. 1). The basin occurs in the Gaúcho Shield and was deposited over mylonitic metamorphic and igneous rocks and metasediments of the Porongos Com-

plex. Fragoso Cesar et al. (in press) argue that the basin was formed after the Neoproterozoic accretion of Gondwanaland. Its site was determined by discontinuities formed during earlier tectonic events.

Major shear zones form the eastern limit of the basin, the Açotéia-Pedras Altas fault, and cut the interior of the basin as the NNE-trending Tapera Emiliano and Espinilho faults, both



Figure 1 - Location and geological map of the study area. Compiled from Gonzalez and Teixeira (1980), Silva Filho (in preparation) and Fambrini (in preparation).

MC: Camaquã Mine. CP: Central point, coordinates $31^{\circ} 55' 30''$ S, $53^{\circ} 19' 98''$ W.

part of the Tapera Emiliano fault system (Fig. 1).

The study area includes the Minas do Camaquã structural high, which hosts sediments of the Santa Bárbara Formation, and continues eastwards to the contact with the Porongos Complex at the base, outcrops of the Guaritas Formation at the top of the regional stratigraphic pile, and the Rodeio Velho andesites which occur between the two. The area has been studied by a number of researchers, but satellite remote sensing methods have only recently been applied (e.g. Ribeiro de Almeida et al., 1995; Silva Filho et al., 1996c).

Vegetation cover is generally poor, with only small areas covered by trees and bushes. Soils are thin and the lithological units are well-exposed. Good correlation was found between the vegetation and the lithotypes present. These regional characteristics suggested that digital processing of the TM-Landsat images would be useful in establishing parameters in regional geological studies.

Based on physiographic and lithologic characteristics of the region, digital image processing techniques should show the spectral responses of the various lithotypes. In addition to simple false-colour composition images, two techniques were employed: Principal Component Analysis (PCA) and band ratios. Before the application of these techniques, careful study of spectral responses of rock types in the available bands 2, 3, 4, 5 and 7 were undertaken. The resulting data helped the understanding of the results of band ratios and PCA, and also in the geological interpretation of the PCA.

The results of this processing are presented and discussed in terms of specific spectral responses of each rock unit, strongly influenced by the textures and density of vegetation. The albedo responses were strongly influenced

by the textures, and were also important in the final interpretation.

GEOLOGY AND STRATIGRAPHY

The basement of the Camaquã basin is formed by various mylonitic rocks derived from granites and associated rocks, and metasediments such as quartzites, marbles and schists, forming the Porongos Complex. The mylonites were formed during the Neoproterozoic accretion between the Piratini and Rio Vacacai terranes and a central plate called Brasiliania (Fragoso Cesar et al., 1994, 1995).

The basin as presently understood (Fragoso Cesar et al., in press) contains two main sedimentary sequences separated by an angular, erosive unconformity (Robertson, 1966; Ribeiro et al., 1966; Fragoso Cesar et al., 1984, 1985; Fragoso Cesar, 1991; Paim et al., 1992; Paim, 1994; Fambrini et al., 1995, 1996a, b; Fambrini, in preparation). The basal Santa Bárbara Formation and the upper Guaritas Formation (using Robertson's (1966) definition), forming the Camaquã Group (Proterozoic-Phanerozoic transition sensu Bowring et al., 1993), both crop out in the study region (Fig. 1).

The Santa Bárbara Formation is predominant in the area of the Minas do Camaquã structural high. It includes two main regressive sequences, an upward-fining rhythmic sandy-pelitic cycle representing turbidites of probably shallow marine origin, and an upward-coarsening cycle formed by conglomerates and pebbly sandstones of coastal and alluvial fans and an alluvial plain (fluvial and braid-delta) facies showing the uplifting of the source areas (Lavina et al., 1985; Faccini et al., 1987; Paim et al., 1992; Paim, 1994; Fambrini et al., 1995, 1996a, b). Local stratigraphy partially adopted in this work was simplified from Gonzalez and Teixeira's

(1980) definition, which divided the Santa Bárbara Formation into four lithological units: (i) fine-grained sandstones and pelites representing the rhythmites, and the upward-coarsening cycles separated into (ii) Lower Arenite, (iii) Conglomerates and (iv) Upper Arenite, as seen in Figure 1.

The Guaritas Formation discordantly overlies the Santa Bárbara Formation, and includes lower sandy-pelitic deltaic, lacustrine, alluvial and eolian, and upper fluvial facies of arid- to semi-arid environments (Paim et al., 1992; De Ros et al., 1994; Paim, 1994, 1995; Fragoso Cesar et al., in press; Silva Filho, in preparation). The latter two facies are prominent east of the Tapera Emiliano fault system. The eolian facies are also important northwest of the Camaquã mines, whereas the upper fluvial units occupy the northern part of the study area (Fig. 1). The Rodeio Velho andesites (*sensu* Ribeiro et al. 1966) are shallow intrusive rocks (Silva Filho et al., 1996a), and are abundant in the study area specially near the Camaquã river and in the southeastern part of the region. Their stratigraphic position is uncertain.

PHYSIOGRAPHY

Relief in the region has a clear litho-structural control. The highest points are formed by basement quartz-mylonite crests in the eastern and southeastern parts of the area. In the same unit, the presence of less quartz-rich rocks leads to the development of V-shaped valleys along foliation trends, with the watersheds occupied by tributaries with a similar profile but orthogonal to the main valleys. Table 1 shows a summary of the principal characteristics of the physiographic attributes of the region.

In the sedimentary domain the highest points occur at the southeastern

limit of the Camaquã Mines structural high, where the upper sandstones of the Guaritas Formation are in angular and erosive unconformity with conglomerates and sandstones of the underlying Santa Bárbara Formation. Higher altitudes are found at the top of plateaus developed over poorly-sorted conglomeratic sandstones of the upper Guaritas Formation, in hills of Santa Bárbara Formation conglomerates at the northwestern and east-northeastern limits of the structural high, and on occurrences of the Rodeio Velho andesites, south and southwest of the high, near the Camaquã river. The lower sectors are mainly in areas occupied by medium- to fine-grained sandstones and intercalated sandstones and pelites of rhythmites of the Santa Bárbara Formation and the lower Guaritas Formation which are less resistant to erosion.

The drainage is less dense in the sedimentary sector than it is in the basement, with a well-defined rectilinear-orthogonal pattern due to deep-cut valleys along fractures in sandstones of the upper Guaritas Formation. In the lower units of this formation the drainage pattern is even less dense, with a weaker litho-structural control resulting in dendritic or rectilinear patterns.

Vegetation covers most of the surface area and is composed of grasses and trees. Areas of thinner cover coincide with quartz-mylonite hill crests in the basement, plateaus of quartz-rich sandstones of the top of the Guaritas Formation near the Tapera Emiliano fault, on top of rudites of the Santa Bárbara Formation in the Camaquã mines, and some parts of the region occupied by the Rodeio Velho andesites, south and southeast of the Camaquã Mines structural high (Table 1).

Dense tree cover is concentrated at the bottom of valleys in the sedimentary terranes; in incised valleys on the basement at the eastern border of the

Table 1 - Physiographic terrane attributes with relation to the rock units exposed in the study area.

Rock units/ Physiographic Terrane Attributes	Vegetation	Soil Cover	Relief	Rock exposure
Calk-alkaline intrusive rocks	Bush and trees, dense	<i>RODEIO VELHO</i> Thick, A and C horizons (argillaceous)	Plateau, high, irregular	In small areas (top of hills, centre and SE of the region)
<i>GUARITAS FORMATION</i>				
Upper Guaritas Fm.	Absent, exposed rocks	No	High tabular plateaus	Widespread
Lower Guaritas Fm.	Grasses and bushes	Thin, C horizon (arenaceous)	Low, dendritic drainage pattern	Some areas on sandstone plateaus
<i>STA. BÁRBARA FM.</i>				
Upper Arenite	Grass, sparse trees	Thin to absent Shallow to absent (thin gravelly C horizon)	Slightly irregular Hills, highest points in the region, rectilinear drainage pattern	Little
Conglomerates	Bush-tree cover			Yes
Lower Arenite	Grass, sparse trees	Thin, C horizon	Low	Little
Sandy-pelitic rhythmites	Grasses with sparse bushes	Thin, A (thin) and C (thick) horizons	Flat, low, large open fields	No
<i>BASEMENT</i>				
Quartzites Porongos Complex	Absent	No	High, quartzite and qz- mylonite crests	Yes, large expositions
Other qz-poor rocks from the Porongos Complex	Bushes, trees and grasses	Thin	Low, V-shaped valleys	No

basin; northeast, east, east-southeast and south of the structural high areas which correspond to the largest exposures of the Rodeio Velho andesites, and in rougher areas over the conglomerates of the Santa Bárbara Formation (Table 1).

Grasses form open fields with sparse bushes and trees and occur in areas of low relief which largely coincide with the basal Guaritas Formation, with sandy-pelitic intercalations and the upper sandstones of the Santa Bárbara Formation, and restricted areas of the Rodeio Velho andesites (Table 1).

The fundamental physiographic feature in the scene which results in spectral responses that are related to underlying geology, is the thin (or absent) soil cover. Pixel compositions result from a mixture between content and type of biomass and of exposed rock.

DIGITAL IMAGE PROCESSING

Landsat TM image (scene WRS 222/81), acquired from the Brazilian National Institute of Space Research (INPE), were employed in this study. Unfortunately only the bands 2, 3, 4, 5 and 7 were available for this study. Pre-processing (for the band rationing) included correction of atmospheric scattering of bands 2, 3 and 4 by the Dark Pixel Subtraction method (Chavez, 1975). Values obtained from the topographic shadows were used, and the correction factors obtained were: band 2, 11; band 3, 9; and band 4, 4. No correction was necessary for bands 5 and 7.

The choice of false-colour combinations was made as much by analysis of correlations (bands 2, 4 and 5, and 4, 5 and 7 were the least correlated) as by the quality of the end product. Although the combination of bands 2, 4 and 5 is theoretically interesting, it did not satisfactorily discriminate the lithotypes as well as the combination of bands 3, 4 and 5. For interpretation, the combina-

tion 457 (RGB) has been chosen as ideal, followed by 435 (RGB). Band 4, with high reflectance from vegetation (which is strongly correlated with the geology in this case) was fixed as the R component due to the ability of the human eye to distinguish its tones. The remaining bands were chosen by trial and error, leading to the combination 435 and 437 (RGB).

In an attempt to reduce the spectral dimension of the group of bands available and to separate vegetation and exposed rock responses, Principal Component Analysis (PCA) was employed. This is one of the most powerful techniques for manipulation of multispectral data, although it is also one of the least understood (Crósta, 1992). Ohara (1982) used the method in digital image processing of the region of the Camaquã mines. He succeeded in separating the lower and upper parts of the Guaritas Formation (in the sense used in our study) in PC3 and PC4 generated from the four bands of MSS-Landsat.

According to Davis (1977, in Loughlin, 1991), PCA is a statistical method which selects successive linear combinations of a group of variables so that in each linear combination the Principal Component (PC) has a smaller variance than its predecessor. The statistical variation in multi-spectral images is related to the responses of the different surface materials such as soil, vegetation and rocks, as well as the radiometric resolution of the detector. In particular, the variance of each subgroup of data - each band - exercises a great influence on the eigen-value, which is a measure of the quantity of information in each PC in relation to the whole group. The PCs are a weighted linear combination of the participation of the original bands eigen-vectors to the formation of each PC. In the present case, the interpretation of PCs is mir-

rored on the Feature-oriented Principal Component Selection (FPCS: Crósta & Moore, 1989), which uses spectral characteristics of specific targets and the quantitative relationship between the original spectral bands and the PC images derived from them (Crósta, 1990). This analysis is undertaken in three stages (Crósta, 1990):

(i) application of PCA through calculation of statistical transformation parameters

(ii) modeling of the spectral response of the materials of interest

(iii) selection of PCs containing the desired information, based on the responses of the materials and on the modulus and signs of the eigen-vector coefficients.

It is practical to transform the modules of the eigen-vectors of each PC into percentages. These percentages give an indication of the probability of encountering areas with responses dif-

ferent from that of the chosen surface material. A positive sign indicates a positive correlation of the grey scale relative to the dark or light response of the PC and the original band. A negative sign indicates the inverse case.

The FPCS will not be rigidly applied in this study because the technique was developed for prospection in residual soils formed by clay minerals and iron oxides, developed over hydrothermally altered mineral deposits. These materials have a specific spectral response. In this study it was empirically found that a relatively characteristic spectral response of many of the units present resulted from physiographical and lithological factors. Using a sample of 100 pixels in each of the bands for each rock type, a differentiated spectral behaviour pattern was found (Table 2), and thus was used to orient the analysis of each PC.

PCA was applied to the five

Table 2 - Arithmetical means of the grey level (DN) of samples representative of the different rock types in the area.

ROCK TYPES	MEANS				
	TM2	TM3	TM4	TM5	TM7
Schists	8,4 ± 1,3	13,1 ± 2,6	32,7 ± 2,0	54,5 ± 5,2	16,6 ± 1,6
Quartzites	11,8 ± 2,9	14,2 ± 3,3	41,5 ± 5,2	62,3 ± 8,7	18,4 ± 3,5
Rhitmites	13,9 ± 0,9	20,0 ± 1,1	50,0 ± 3,7	76,6 ± 6,8	22,5 ± 2,1
Lower arenite	9,9 ± 1,6	12,7 ± 2,1	42,2 ± 6,0	58,6 ± 7,1	16,1 ± 2,0
Conglomerate	9,2 ± 0,7	12,7 ± 1,1	36,8 ± 3,3	55,9 ± 5,1	16,5 ± 2,0
Upper Arenite	12,6 ± 1,0	17,8 ± 1,0	44,7 ± 4,8	70,9 ± 8,6	20,9 ± 2,3
Rodeio Velho andesites	7,8 ± 1,2	9,8 ± 1,9	37,0 ± 3,0	46,1 ± 8,5	12,4 ± 3,4
Lower Guaritas Fm.	11,6 ± 2,7	18,1 ± 3,1	38,6 ± 5,6	72,0 ± 11,0	23,3 ± 4,8
Upper Guaritas Fm.	10,4 ± 2,5	15,3 ± 4,3	33,8 ± 4,1	60,9 ± 13,4	19,5 ± 5,9

available bands with no pre-processing. The resulting PCs were subjected to linear contrast stretching, while a laplacian + original filter with a 5x5 kernel was applied to PC1.

The selection of PCs for colour composition images was obtained after

analysis of the information content of each one. Thus, the composition PC1PC2PC4 (RGB) gives the greatest volume of information due to, respectively, the texture (albedo), the vegetation and exposed rock, while the remaining PCs (PC3 and PC5) did not

yield useful information for this study.

The eigen-values and eigen-vectors of each image PC are given in Table 3.

Table 3 - PCs eigen-vectors and eigen-values for samples generated for PCA.

PC	Bands Eigen-value(%)	TM2	TM3	TM4	TM5	TM7
		Eigen-vector (%)				
PC1	85	7,7	12,6	16,5	46,7	16,5
PC2	12	2,0	-7,2	60,8	-13,7	-16,3
PC3	02	22,5	45,5	2,2	-20,8	9,0
PC4	01	-5,9	-16,0	8,9	-16,6	52,6
PC5	00	63,1	-30,0	-5,6	0,0	-0,7

The PCs were then combined in triplets and enhanced using a linear contrast stretch. The RGB triplets were interpreted on the basis of eigen-values, eigen-vectors and known terrane features.

RESULTS AND DISCUSSION

Analysis of the eigen-vectors (Table 3) of image PC1 (Fig. 3) confirm the expected results. Band 5 has the largest variance of all original bands and the greatest contrast, and contributes 46.7% to the PC1.

PC1 presents positively correlated information from all bands. Such information refers to illumination gradients of the area – the topographic shadowing – and the natural albedo of the surfaces. In PC1 (Fig. 2), the light pixels represent (i) areas with little or no vegetation, in which predominantly quartz-rich rocks crop out; (ii) hilltops formed by the upper Guaritas Formation, (iii) parts of the lower Guaritas Formation east-southeast of the Tapera-Emiliano Fault, and (iv) quartzite crests of the Porongos Complex. Grass vegetation cover and flat relief areas occur predominantly over sandy-pelitic rhythmites of the Santa Bárbara Formation and appear in

the image as light pixels. Areas of slightly irregular relief occurring over fine sandstones of the Upper Arenite also give light pixels. The reason seems to be that the grass cover acts as a homogeneous reflector. Table 4 summarizes this information providing an easy visualization of the main contribution to PC1 based on the image terrane attributes.

Dark pixels in PC1 (Table 4) are related to the exposures of the Rodeio Velho andesites and the quartz-poor rocks of the Porongos Complex. These surfaces have bush and tree cover and are irregular. Dark pixels also occur on outcrops of the Santa Bárbara Formation conglomerates which have bush-tree cover and a naturally irregular texture formed by fractures and erosion developed at the top of units. Mid-tone pixels are found over exposures of the lower Guaritas Formation, where the density of vegetation is greater.

The most important contribution to PC2 (Fig. 3) is from band 4 (Table 3), which is probably due to the spectral response of vegetation. Comparison of PC2 with the ratio 4/3 (Fig. 4) shows that they are similar. Table 4 gives an idea about the PC2 contribution based on the image terrane attributes. Light pixels are related to outcrops of andesite, sandy-pelitic rhythmites of Santa Bárbara Formation, sandstones of the lower Guaritas Formation, together with some areas of the Porongos Complex. Dark pixels are clearly related to rock outcrops such as ridges of quartzites of the Porongos Complex, of the lower Guaritas Formation close to the large occurrence of andesites in the centre-south of the area, and of the upper Guaritas Formation. Intermediate-tone pixels occur over the lower Guaritas Formation and conglomerates of the Santa Bárbara Formation.

In the generic spectral curve of vegetation, the areas of lower reflectance



Figure 2 - Image PC1 showing textural aspects of the study area. Note light pixels representing absence or little vegetation, and dark pixels the opposite situation. Further explanations in the text.



Figure 3 - Image PC2. The image confirms the predominance of the vegetation response (light pixels).

Table 4 - Stratigraphic units versus PCs and Terrain attributes.
L = light pixels; M = medium-gray pixels; D = dark pixels.

	PC1	PC2	PC3	Vegetation	Soil Cover	Relief	Rock exposure
Rock outcrops	L	D	L				
Soil cover	L	L	L				
Vegetation	D	L	L-M				
Rock Units							
RODEIO VELHO Andesites	D	L	L	Bush and trees	Thick	Plateau, high, irregular	Few parts
Upper GUARITAS FM.	L	D	L	Little or absent	No	Plateau, high, flat	OK
Lower GUARITAS FM.	L-M	L	D	Grass and bushes	Thin	Low	Some parts
Upper Arenite	L	L-M	D	Grass, sparse tree	Thin to absent	Slight irregular	Little
Conglomerates	D	L-D	L	Bush-tree cover	Shallow to absent	Hills, high	OK
Lower Arenite	L-M	L-D	D-M	Grass, sparse tree	Thin	Low	Little
Sandy-pelitic rhythmites	L	L	D	Grass	Thin	Flat, low	NO
Quartzites crests of the PORONGOS COMPLEX	L	D	L	Absent	No	High, quartzite and qz-mylonite crests	OK
Other qz-poor rocks from the PORONGOS COMPLEX	D	L-M	D	Bushes, trees and grasses	Thin	Low, V-shaped valleys	NO

tance correspond, in increasing order, to TM bands 1, 3, 2 and 7, while the areas of greater reflectance correspond, in decreasing order, to bands 4 and 5. The matrix of PCA eigen-vectors shows that most information from band 4 - the vegetation - is concentrated in PC1 and PC2. The greatest part of the information contained in band 5 is concentrated in PC1. The PC3, PC4 and PC5 have greater contributions from bands 3, 7 and 2, respectively. Theoretically, they have the greatest chance to concentrate information related to the lithological component of the pixels. Similar analysis directed towards the more specific response of Fe-oxides and clay minerals were undertaken by Loughlin (1991) to test the FPCS technique.

In PC4 (Fig. 5), the largest contribution is due to the band 7 (52.6%), followed by band 5. In these bands, mainly the TM7 band, the lithol-

ogy spectral response is different, probably due to clay mineral contributions. In this PC (Table 4) bright pixels appear at the top of hills over the upper Guaritas Formation, specially in the centre-north of the area and near the Tapera-Emiliano Fault, where quartz-rich units of the lower Guaritas Formation occur. Further north, these units are covered by units of the upper part of the formation. Mid-tone to bright pixels define the tops of many hills of conglomerates of the Santa Bárbara and upper Guaritas formations in the western part, near the Tapera-Emiliano Fault and the top of quartzite crest of the Porongos Complex. Mid-tone pixels also define the areas of the andesites in the southern part and SE of the Camaquã Mines structural high. Mainly dark pixels occur over the sandy-pelitic rhythmites and the Upper Arenite of the Santa Bárbara Formation, as well as in areas of



Figure 4 - Ratio TM4/TM3 - vegetation cover occurs as light pixels and is very similar to the image of Figure 3 (PC2).

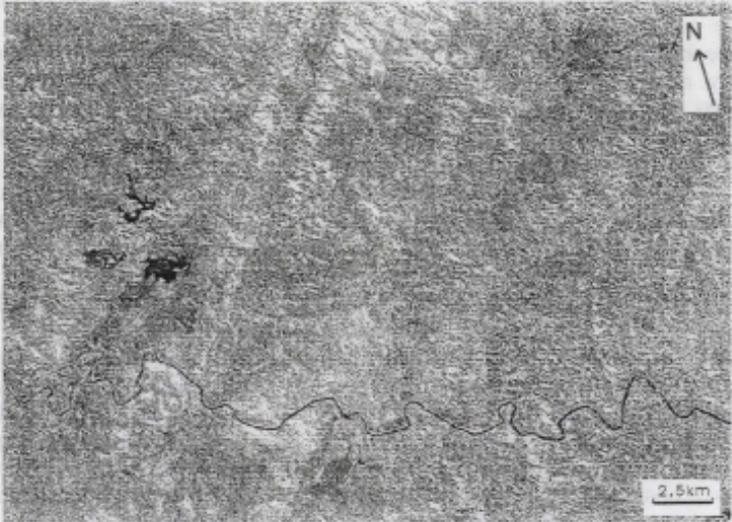


Figure 5 - Image PC4 - differences in the ratio vegetation/exposed rock (light pixels associated to rock outcrops).

the lower Guaritas Formation in the NE, central-E and central-SE sectors. With the exception of the andesite exposures in this PC, the variation of the intensity of the pixels is the inverse of that for PC2. Knowing the physiography, the brighter areas of PC4 are formed by pixels of the less-vegetated areas on crests formed by quartz-rich rocks.

Examination of RGB triplets combining PC1, PC2 and one of the remaining components showed that the PC1-PC2-PC4 triplet is best for showing the lithological and structural features (Fig. 6).

Visual examination of the PC1PC2PC4 composition (Fig. 6) allows the easy separation of many of the units present in the area. It has a wealth of textures, but the main feature is the differentiated spectral response. The behaviour of the different units in each one of the PCs has been described above. The combination of these PCs can be explained by the theory of additive colours. In general the basement appears in light green colour and has a very rough texture, and the quartzite crests with N trending give magenta colour due to the rock exposition. The two main outcropping sedimentary units in the study area can be separated into sub-units which correspond to sedimentary facies of the larger units.

The Santa Bárbara Formation was separated into three sub-units as follows: (i) the sandy-pelitic rhythmites appear in yellow or reddish-yellow and have a smooth texture; (ii) the conglomerates and sandstones of the Upper Conglomerate and the Lower Arenite appear in green or, where vegetation is low or absent, in magenta. PC1 and PC4 have large contributions, and a low PC2 contribution reflects grass cover. The texture of these rock types is very rough. The Upper Arenite has a yellow to reddish-yellow colour, but is distinguished from the sandy-pelitic rhyth-

mites by having a rougher texture.

The Guaritas Formation was separated into two sub-units: the lower unit is red, with a high albedo as a consequence of thin vegetation, shallow soils and gentle relief, while the upper unit is magenta with a large contribution from PC4 and a high albedo in PC1. This is a result of rock exposures of predominant quartzose sandstones.

Finally, the Rodeio Velho andesites stand out by the intense green colour and smooth texture, a result of the tree cover, thicker soils and more homogeneous lithology.

The PC1-PC2-PC4 triplet represents the interaction of the three principal components of the physiographic features which are influenced by the regional geology: relief, type of vegetation and the proportion of vegetation to exposed rock, respectively, as well as the spectral response of the rock types.

For comparison with Figure 6, the false-colour composition 435 (RGB) is shown, in which some of the lithostratigraphic units can be identified, although lacking the richness of spectral information given by the combination of PCs. The contrast-stretched 435 (RGB) triplet (Fig. 7) shows a predominance of cyan, red and magenta hues. The latter are associated with vegetation cover over parts of the Porongos Complex basement, the Rodeio Velho andesites and conglomerates of the Santa Bárbara Formation. Pure cyan hues are associated with both, flat summits formed by the upper sandstone units of the Guaritas Formation, and with quartzite crests of the Porongos Complex. The strong cyan contribution might reflect the unimportance of vegetation here, since the response of the TM4 band is usually used as an index of the biomass density on composition of the reflecting surface (e.g. Sabins, 1986). This is, however, incorrect since other results demonstrate the importance of the vegetation



Figure 6 - Triplet TM4TM3TM5 in RGB space.



Figure 7 - Triplet PC1PC2PC4 (RGB).

in discriminating between the rock types.

The map presented in Figure 8 is the result of the geological interpretation of the image obtained with the

triplet PC1-PC2-PC4 (RGB), shown in Figure 6, with the aid of the other processed images, such as the false-colour combinations 457 and 435 (RGB).



Figure 8 - Geologic sketch based upon PC1PC2PC4 (RGB) colour composition.

CONCLUSIONS

The results obtained confirm that Principal Component Analysis (PCA) and band ratios techniques were very adequate for establishing the preliminary geologic sketch of the study area, and also for helping the final field work and mapping of sedimentary facies.

The geographical distribution of the units suggests structural control on the depositional environments. The drainage has a well-defined rectilinear-orthogonal pattern due to deep-cut valleys along fractures in sandstones of the upper Guaritas Formation. In the lower units of this formation the drainage pattern is even less dense, with a weaker litho-structural control resulting in dendritic or rectilinear patterns.

The vegetation contribution is the main spectral discriminatory feature of the different lithotypes, although the

texture also helps as does, to a lesser extent, the presence of exposed rock. The type of vegetation is intimately associated to the lithotypes exposed in the study area. Thin soil cover helps in discriminating the rock types, and even the sedimentary facies. Principal Component Analysis (PCA), after careful sampling and subsequent definition of the spectral behaviour of the various rock types, is a very useful tool in mapping of sedimentary formations.

The PC1 component reflects textural patterns related to the relief and the different albedos of vegetation and rock outcrops. In PC2, the spectral response is due to the vegetation. In PC4, the spectral response is the sandstones and conglomerates of the two sequences, together with quartzite hills of the basement complex.

The geological interpretation of the C1-C2-C4 triplet resulted in a map

(Fig. 8), which is very similar to the geologic map devised after extensive field work (Fig. 1). This triplet is a powerful tool for identifying sedimentary facies or units in basin-scale studies.

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