IDENTIFICATION OF HYDROTHERMAL ALTERATION USING SATELLITE IMAGES IN AREAS WITH DENSE VEGETATION COVER

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ABSTRACT

TM images were used in order to characterize areas with hydrothermal alteration. Processing of the images included principal components analysis and False color composition (RGB). The studied area is located in the western border of the Mexican Volcanic Belt and hosts still unexploited ore deposits (mainly opal and precious metals) of hydrothermal origin. The stratigraphic column includes products of the volcanic activity that formed the Sierra Madre Occidental during the Tertiary, and of the recent volcanic activity related to the still active Ceboruco Volcano. The main problem is to differentiate the hydrothermally altered rocks from vegetation covered areas in the satellite image. The band ratios did not yield good results in removing the spectral effect of the vegetation cover in areas that contained hydrothermally altered rocks, this was due to the high correlation between the bands as was shown when they were analyzed using the principal components approach. The removal of the vegetation spectral effect was done using the Cróssta technique for bands: 1, 3, 4, and 5, for oxides analysis; and 1, 4, 5, 7, for hydroxyls analysis. All the zones of alteration mapped in the field coincide with the areas marked as hydrothermally altered in the resulting images.

1. INTRODUCTION

Remote sensing techniques have been used in the early stages of exploration in order to reduce the extension of the area to be studied with geophysical and geochemical methods (Bhan, 1983; Guangquing, 1983; Podwysoki, et al., 1983). The most important surface features for geothermal and mineral exploration that can be mapped with satellite images are the main structures and areas that contain hydrothermal alteration minerals (Buckingham and Sommer, 1983; Kaufmann, 1988; Drury and Hunt, 1989).

Hydrothermal alteration minerals (mainly hydroxyls) and their weathering products (mostly oxides) are recognizable by the processing of satellite images due to the reflectance anomalies that are present in the blue, red and middle infrared bands (Thematic Mapper bands 1,3,4,5 and 7). TM bands 5 and 7 are especially useful for this purpose. In this study we will show the applicability of multispectral satellite image processing in identifying hydrothermally altered rocks in an area covered by diverse vegetation types: crops and shrubs in the lowland, and small trees in the higher elevation land.

2. GEOLOGIC SETTING AND DISTRIBUTION OF HYDROTHERMAL ALTERATION

The study area is located in the border between the Sierra Madre Occidental and the Mexican Volcanic Belt. between 20°53'

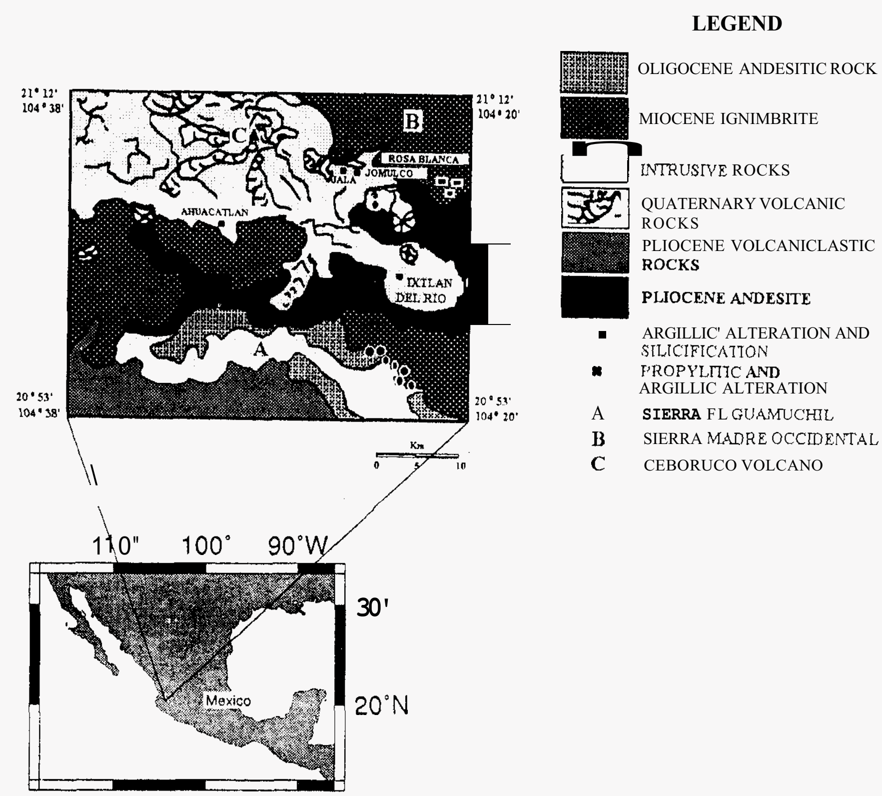

Fig. 1. Location of the studied area, simplified geology (after Romero et al., 1991), and mapped hydrothermal alteration areas.

and 21°12'N and 104°20' and 104°38'W. It comprises an area of 1166 km^2. The surface geology in the area (Fig. 1) is characterized mostly by igneous rocks, with ages ranging from Tertiary to Recent; however, rare outcrops of older sedimentary and metamorphic rocks are also found.

The fault patterns are represented by the NW-SE and the NE-SW directions that form fault pairs and resulted in the formation of the Ceboruco and Amatlán de Cañas tectonic basins (Ferrari et al., 1993). The structures in these basins are similar to those of a graben. The Ceboruco basin is formed by three parallel normal faults with strike N120E, it is within this basin that the Ceboruco Volcano is located. The Amatlan de Cañas basin is formed by two large normal faults, one to the East with strike N150E and the one to the west with strike N80E (Ferrari et al., 1993).

Samples were collected from hydrothermally altered rocks during two field trips to obtain control points for the image processing at the points marked in Fig. 2, in the towns of Jala, Jomulco, Rosa Blanca and in the Sierra El Guamuchil. In the Sierra El Guamuchil a correlation was observed between alteration and the occurrence of intrusive rocks. The alteration mapped is mainly contained in the rocks that belong to the Sierra Madre Occidental along the NW-SE and NE-SW faults. Silicification, argillic and propylitic alteration types were identified associated with the opal mines and the precious metals mineralization. The northern part is characterized by opal and kaolin mines, and argillic alteration areas of more than 250 m^2 are common. Most argillic alteration areas also show intense oxidation, which makes them easier to identify with the infrared images as the iron oxide spectra present anomalously high reflectance values in the band-5 (Hunt, 1977). Propylitic aiid argillic alteration types associated with the gold-silver veins are more difficult to identify because they are encountered in the southern part of the studied area (Sierra El Guamuchil) that is covered by vegetation and the outcrops extension is generally restricted to a few tens of square meters. However, alter the data processing, the control points could be identified in the images.

Fig. 2. First principal component shows the main features in the image of the studied area. Control points where samples of hydrothermally altered rocks were collected during the field trips are marked with asterisks. A, B and C denote the Sierra del Guamuchil, the Sierra Madre Occidental and the Ceboruco Volcano, respectively.

3. IMAGE PROCESSING

The image processing techniques applied in this work were selected on the basis of the characteristics of the area and the objectives of the study. The processing was done on a subimage (1024 x 1265 pixels) obtained from the SW quarter of the TM image (Path 030, Row 045) taken by the Landsat 5 in April 1991. This subimage will be referred as the Ceboruco subimage.

Two software packages were used in the processing of the image: IDRISI (A Grid-Based Geographic Analysis System) release 4.2, developed by the Graduate School of Geography from Clark University, aiid SPIPR (Remote Sensing Interactive Personal System) release 2.0 developed by the IBM Scientific Center (Mexico City) and the Mexican National Institute of Geography and Statistics (WEGI).

The spectral characteristics of the hydrothermal and supergene alteration minerals commonly found in fossil and active geothermal systems allow classification into two groups. The first group contains the hydroxyls (clays and micas) and the hydrated sulfates (gypsum and alunite); and the second includes the iron oxides (hematite, goethite and jarosite). The first group (we will denote them as hydroxyls) present typical high reflectance in the TM

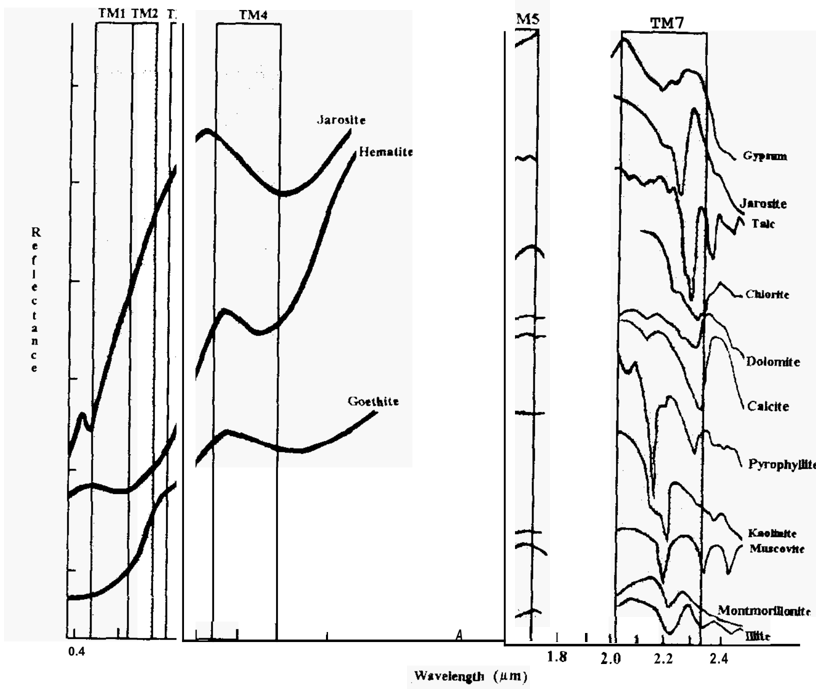

Fig. 3. a) Characteristic spectra of typical minerals found in hydrothennally altered rocks (After Hunt, 1977, 1979; Hunt and Ashley, 1979). Shaded areas indicate the Thematic Mapper bands.

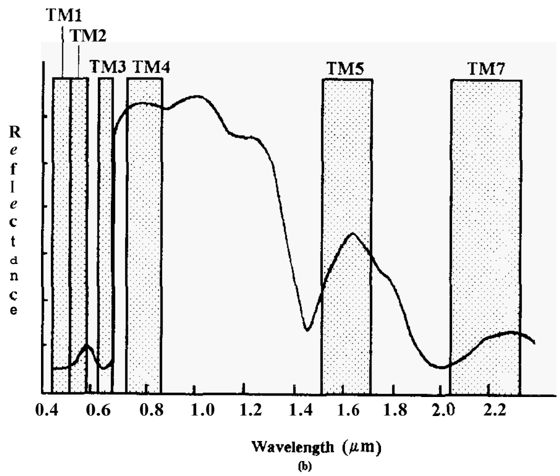

Fig. 3 b) Spectral response of vegetation. Shaded areas indicate the Thematic Mapper bands.

band 5 (TM5) and high absorption in band 7 (TM7), while the oxides (group 2) show high reflectance in bands 3 (TM3) and 5 (TM5), and an absorption anomaly in band 1 (TM1) (Hunt, 1977, 1979; Hunt and Ashley, 1979; Wester, 1992) (Fig. 3). The alteration minerals spectra overlap with the spectrum typical of the vegetation in the area which has the highest reflectance values in band 4 (TM4), but has also relatively high reflectance in bands 5 and 7 (TM5, TM7). The overlapping makes it difficult to differentiate areas with a vegetation cover from areas that contain hydroxyls and oxides. Their identification using band ratios and false color composites was not possible, therefore other techniques were applied to the subimage in order to separate the hydrothermally altered areas from the ones covered by vegetation. The one that proved to be useful in this study was the Crósta Technique (Feature Oriented Principal Component Analysis) (Crósta and McM. Moore. 1989). The Crósta Technique is based on the Selective Analysis of Principal Components developed by Chavez and Kwarteng (1989) and it has been applied to separute the spectral response of vegetation from that of oxides and hydroxyls. The technique allows the identification of the principal components that contain spectral information of any materials whose spectral anomalies coincide with the analyzed image bands, and also the contribution of each of the original bands used **in** the principal component analysis (PCA).

In this study we used a modification of the Crósta 'Technique that utilizes in the PCA only the image bands that contain spectral features that characterize the minerals that are searched for and the vegetation to be removed (Loughlin, 1991). The band TM4 contains the largest reflectance anomaly that characterizes vegetation, therefore this band was included in the analyses for oxides and hydroxyls. For the mapping of oxides the bands TMI, 'TM3 and TM5 were used (plus the TM4) as they include the features necessary to identify the oxide bearing minerals as explained above. The hydroxyls were mapped including the bands TM1, TM4, TM5, and TM7, in ordcr to include the absorption (TM7) and reflectance (TM5) anomalies characteristic of clays, sulfates, carbonates and other hydroxyl bearing minerals.

4. RESULTS AND DISCUSSION

Tables 1 and 2 show the statistical variance percentage that corresponds to each component, the characteristic value and the eigenvzctors for each band in each component, for the oxides and hydroxyls analysis respectively. From Table 1 it follows that the second principal component (PC2) contains mostly information on the vegetation cover as the eigenvector for the TM4 band is 93.40. This large positive value indicates that the vegetation covered areas will appear as bright pixels in PC2. The most important contributions to PC4 in the oxides analysis (Table 1)come from the TM1 and TM3 bands: 71.60 and -69.11, respectively. The signs indicate that the oxides will be represented in dark pixels as their spectrum has an absorption anomaly in TM1 and a high reflectance anomaly in TM3. Therefore, in order to have them shown in bright pixels, it is necessary to obtain the PC4 inverse image, which we will call the "O" image (Fig. 4). In this image the brightest pixels will represent the oxides-bearing rocks.

The hydroxyls analysis eigenvectors are shown in Table 2. As in Table 1, PC2 contains information about vegetation in bright pixels, and PC4 is the component thnt contains more information related with the characteristic spectral features of the hydroxyls. The eigenvectors corresponding to the TM5 and TM7 bands have high values with opposite signs (34.79 and -73.85) that correlate well with their high reflectance in TM5 and high absorption in TM7. According to these values the hydroxyl bearing rocks will show in PC4 as bright pixels. This will be referred as the "H" image (Fig. 5).

Table 1. PRINCIPAL COMPONENT ANALYSIS FOR OXIDE MAPPING

COMPONENT	PC1	PC2	PC3	PC4
% VARIANCE	86.95	6.98	5.59	0.47
EIGENVECTOR	1196.86	96.04	77.01	6.52
TM1	25.36	-0.0 1	65.03	71.60
TM3	36.43	8.17	61.88	-69.11
TM4	28.43	93.40	-20.00	8.20
TMS	84.97	-34.75	-39.25	5.53

Table 2. PRINCIPAL COMPONENT ANALYSIS FOR HYDROXYL MAPPING

COMPONENT	PC1	PC2	PC3	PC4
% VARIANCE	sx.22	7.43	3.76	0.59
EIGENVECTOR	1298.50	109.41	55.32	8.64
TM1	24.16	-10.94	77.91	56.79
TM4	25.81	92.38	19.73	-20.25
TM5	82.01	-5.99	-48.25	34.19
TM7	44.99	-36.19	30.15	-73.85

Fig. 4. Oxide mapping after processing using the Crósta Technique. Bright areas denote oxide bearing rocks. A, B and C as in Fig. 2

Fig. 5. Hydroxyl mapping after processing using the Crósta Technique. Bright areas denote hydroxyl bearing rocks. A, B and C as in Fig. 2

The results obtained separately for oxides and hydroxyls must be combined in order to map hydrothermal alteration, this may be achieved by adding (overlay of the two images with addition of corresponding pixels) the "O" and the "H" images which yield as a result an image ("O+H") that will represent the hydrothermally altered areas as bright pixels (Fig. 6).

The comparison of the "O", " H and "O+H" images with the alteration data collected in the field shows that the best correlation is obtained for the "O+H" image. The oxides image includes bright pixels that do not represent hydrothermally altered rocks but exposed soil on agricultural land which was prepared for planting at the time when the image was obtained. Also when hydroxyls are mapped, high reflectance anomalies are obtained for the Ceboruco volcano recent lava flows where hydrothermal alteration was not

Fig. 6. Hydrothermal alteration mapping ("O+H" image) as the addition of oxide "O" and hydroxyl " H images. **A,** B and C as in Fig. *2*

observed during field mapping. It was found that this is caused by lichen growing on the surface of the rocks (Satterwhite et al., 1985). The effect of soils and recent lava flows is reduced when the "O" and "H" images are added and only areas that include both hydroxyls and oxides are shown as bright pixels.

5. CONCLUSIONS

The spectral characteristics of vegetation, hydrothermal minerals and their weathering products make it difficult to differentiate hydrothermally altered rocks from areas covered with vegetation using multispectral satellite images. Therefore special methods must he applied in order to map rocks that contain oxides and hydroxyls. Band ratios do not give good results because the vegetation reflectance is too high in the middle infrared where the main characteristic features of the hydrothermal minerals spectra occur. The spectra overlapping problem is solved by applying the principal component analysis to the four TM bands in the visible and infrared regions of the electromagnetic spectrum that contain the high reflectance and absorption anomalies typical of the minerals found in hydrothermally altered rocks.

This modification of the Crósta Technique proved *to* be useful for mapping hydrothermally altered rocks in the studied area. It reduced the spectral effect of the vegetation and enhanced the spectral anomalies of the oxide and hydroxyl bearing rocks. This was done for an area that contained three vegetation types with distinct spectral features.

The non-alteration features included in the "O" and "H" images were successfully reduced in the "O+H" image, obtained by adding the oxide and hydroxyl images and resulting in the mapping of the minerals characteristic of hydrothermally altered rocks.

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