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Analyses of Landsat Thematic Mapper Images of the Berenguela-Charaña area, Bolivia

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INTRODUCTION

Landsat Thematic Mapper (TM) data have been effective in mapping hydrothermally altered rocks in arid and semi-arid terrains (Podwysocki et al., 1985; Knepper and Simpson, 1992; Rowan et al., in press). In the central Andes, epithermal volcanic-hosted deposits are often associated with hydrothermal systems that have significant surface expressions detectable through Landsat TM image evaluation.

In the present study, analysis of Landsat Thematic Mapper (TM) images was used to augment conventional methods of investigation for volcanic-hosted epithermal precious and semi-precious metal deposits in the Neogene-quaternary volcanic complexes in western Bolivia. TM data were digitally processed and enhanced to distinguish lithologic units, to map hydrothermally altered rocks, and to identify regional tectonic and volcanic morphological features (Figure 1). After field investigations, spectral measurements of representative samples were analyzed to identify and verify the spectral responses displayed in the TM images. These analyses provided guidance for improving image processing methods, enhancement techniques, and band ratio selection.

The intention of this study was to 1) map hydrothermally altered rocks at a scale of 1:50,000; 2) investigate the spectral properties of epithermal volcanic and sedimentary rocks typical of the central Andes; 3) select TM band combinations and TM band ratios to assist in geologic mapping near Berenguela-Charaña; and 4) field check the results of the TM image interpretation.

GEOGRAPHIC AND GEOLOGIC SETTING

The detailed study area is located just east of the Bolivian Cordillera Occidental, in the highland plateau known as the Altiplano. The study area is located in the Pacajes Province in the Department of La Paz, approximately 160 km southwest of the city of La Paz and 40 km northeast of the town Charaña. The area includes the village of Berenguela, and the following prominent peaks: Cerro Cerke, Cerro Wila

Kkollu, Cerros Huaricunca, Cerro Antacahua located to the north, and bordered on the west by the Española deposit near Cerro San Jeronimo (Figure 2). The detailed study area encompasses approximately 1,400 square kilometers. The elevation ranges from slightly less than 4,000 meters to over 5,100 meters above sea level.

The region is part of a high altitude desert where the dominant vegetation consists of low shrubs, mosses, and grasses. The three dominant genera are *Estipa spp.* (tholla),*Azorella spp.* (yareta), and *Parastrepha spp.* (paja brava). Vegetation is estimated to cover as much as 40 percent of the ground surface but averages about 30 percent.

The Berenguela-Charaña area consists of Neogene volcanic rocks and intrusive rocks, as well as Paleogene sedimentary units. The region is dominated by andesitic-dacitic stratovolcanoes, volcanic domes, and ash-flow tuffs. According to Erickson et al., (1987), epithermal volcanic-hosted gold-silver deposits are commonly associated with Neogene-Quaternary volcanic centers, and many of the deposits are extensively hydrothermally altered, which is typical in southern Peru, western Bolivia, and northern Chile.

DESCRIPTION OF DATA

The Landsat Thematic Mapper sensor records reflected solar radiation in six channels in the 0.45 and 2.35 micrometers region and a seventh band in the thermal infrared. The first three bands are located in the visible range, whereas TM 4,5, and 7 are located in the near-infrared (NIR) wavelengths. The digital data are organized in a matrix of picture elements (pixels) with each pixel corresponding to an area approximately 30 metes by 30 meters on the ground. Each pixel is represented by one digital number (DN), which represents the average spectral intensity integrated over the band or channel width. The location of the TM bands in the electromagnetic spectrum are listed below:

BAND	REGION IN MICROMETERS	
TM 1	.45-.52	(blue)
TM 2	.52-.60	(green)
TM 3	.63-.69	(red)

TM 4	.76-.90	(NIR)
TM 5	1.55-1.75	(NIR)
TM 6	10.3-12.5	(thermal)
TM 7	2.08-2.35	(NIR)

Digital data collected by the Landsat Thematic Mapper sensor on May 15, 1985 was processed. The four quarter scenes that were processed are shown in figure 1. Each quarter scene covers approximately 8,100 sq. km. Image products produced for each quarter scene include: a black-and-white image of a single TM band for regional geologic structural analysis at a map scale of 1:250,000; a false color composite (FCC) of three TM bands for lithologic discrimination at 1:250,000-scale; and a color-ratio-composite (CRC) of a smaller area of interest at 1:50,000-scale. The CRC images were chosen to highlight hydrothermally altered rocks with potential mineralization. Only the results of the Berenguela subset area will be presented here.

The digital TM data were processed using a Sun workstation and a personal computer system. For the detailed study of the Berenguela area, quadrant two of the TM scene located at Path 002/Row 072, identification number Y5044014114X0, was digitally enhanced and printed to map scales prior to visiting the field area in 1990.

IMAGE PROCESSING TECHNIQUES

The main objective of the image processing for the Berenguela-Charaña area was to facilitate the delineation of hydrothermally altered rocks. Digital enhancement techniques included: application of an atmospheric scattering correction, a digital snow mask and water mask, a linear contrast stretch, and the production of TM band-ratio images. Later enhancements, chosen after field investigations, included a vegetation mask and different ratio selections.

Haze causes scattering of visible-wavelength radiation and low image contrast, and the correction technique used reduces these effects, thereby increasing image contrast.

In the CRC images snow covered areas can be confused with rocks of interest and, therefore, it is beneficial to digitally eliminate the effects of snow before producing ratio images. This enhancement technique identifies snow based on its spectral characteristics and, then, assigns these pixels to a DN value of 0, or black, thereby eliminating possible ambiguities. Water is masked in similar fashion. By applying digital masks, the spectral response of the rock and soil units is enhanced by using the full dynamic range of gray levels.

The TM sensor is designed to accommodate the highest and lowest expected radiance over all scenes and, therefore, any particular scene only uses a small portion of the available dynamic range of grey levels. Linear contrast stretching of the data greatly improves the contrast of the original brightness values.

TM band ratios are created by dividing one TM band by another of the same area. Three ratios are combined and displayed in red, green, and blue to create a color-ratio-composite image. Ratio images accentuate spectral differences and reduce brightness variations related to topographic slope and albedo differences (Rowan et al., 1974).

Color-ratio-composite images using TM ratios 5/7, 3/1, and 4/3 displayed in red, green, and blue, respectfully, were produced and evaluated in the field in 1990. TM ratio 5/7 shows spectral reflectance differences between rocks that contain hydroxyl-bearing minerals and rocks that lack these minerals (Podwysocki et al., 1985). Mg-OH and Al-OH minerals have strong and distinct absorption features between 2.0 and 2.5 micrometers (TM band 7). Carbonates also have strong absorption features between 2.30 and 2.35 micrometers. Rocks and soils that contain clays, micas, sulfates (alunite, jarosite), and carbonates have high DN values in TM 5 relative to TM 7 values and, therefore, result in high values in TM ratio 5/7 values. It should be noted, however, areas with carbonate rocks and/or soils cannot be distinguished from areas that contain hydroxyl-bearing minerals because of the broad TM spectral bands.

Healthy green vegetation also produces a high response in the TM ratio 5/7, because absorption by water in the leaves causes lower reflectance at longer wavelengths. To distinguish vegetation from other surface materials, TM ratio 4/3 was included in the CRC images. In the TM 4/3 ration, vegetation responds with high values because of the strong chlorophyll absorption feature centered near 0.68 micrometers (TM 3), which dramatically contrasts with the high reflectance of green vegetation due to scattering by leaf cell structure in the near-infrared between 0.80 and 1.30

micrometers (TM 4 region). Most rocks and soils have low DN values in the TM 4/3 ratio, which eliminates the confusion between hydroxyl-bearing minerals and vegetation. The expected vegetation response, then, would be high TM 5/7 values, as well as high TM 4/3 values.

TM ratio 3/1 was chosen to distinguish limonitic areas from nonlimonitic areas. Electronic transitions in iron minerals produce diagnostic spectral features in the visible range of the electromagnetic spectrum, which result in decreasing reflectance toward shorter wavelengths. Therefore, limonitic areas yield higher DN values in TM ratio 3/1 than those of nonlimonitic areas.

In limonitic areas that also contain clays, sulfates, or other hydroxyl-bearing minerals high values are expected in both TM ratios 5/7 and 3/1. Areas defined as being potentially hydrothermally altered have high values in TM ratios 5/7 (red) and 3/1 (green), but low values in TM ratio 4/3 (blue), and appear yellow (red + green) in the images.

TM color-ratio composites of 5/7, 3/1, and 4/3 were used to guide the field investigations. However, significantly more vegetation was encountered than anticipated in this area. The DN range of vegetation in TM 5/7 is similar to that of rocks containing hydroxyl-bearing minerals. this limits the effectiveness of contrast stretching to display hydrothermally altered rocks. The author concluded that the interpretability of the TM ratios could be improved by applying a digital vegetation mask before ratioing the TM bands and, then, stretching the ratios.

To define the pixels affected by vegetation, a color-infrared (CIR) image consisting of TM bands 4, 3,2 in red, green, and blue respectively, and the TM ratio 4/3 were examined. Vegetated areas in the CIR appear red and correspond with the highest DN values of the TM ratio 4/3. Pixels representing vegetation were assigned a DN value of zero which was used to mask vegetation in all the individual TM bands. By applying a digital mask, the contrast was increased in nonvegetated areas and greatly reduced ambiguities between altered areas and vegetated areas. For a subset of the Berenguela TM scene, a vegetation mask was applied to the individual bands, and subsequently, ratio composite images were created.

Applying the vegetation mask improved our ability to interpret the geology from the resultant CRC image. More discrimination was achieved among the altered rocks and within the unaltered rocks. Applying a vegetation mask to the data also allowed us to eliminate TM ratio 4/3 and to include another ratio, such as 5/4 or 7/4, in the color-ratio-composite image. These ratios contain pertinent spectral information that improved separation among unaltered rock types and facilitated distinguishing compositionally different hydrothermally altered rocks.

Processing of the final image was based on analysis of spectral reflectance measurements of field samples. These spectral data were convolved to the TM band equivalent values by sampling each spectrum using the appropriate TM band filter response curve. From the resultant values the following TM equivalent ratios were calculated: 5/7, 3/1, 5/1, 5/4, 7/4, and 5/2. Plots for several areas of interest were then used to identify the optimum ratios for distinguishing altered rocks from unaltered rocks (Figs. 5 and 6). In figures 5 and 6 note that the difference between the altered and unaltered rocks is substantially larger for the TM 5/1 than the TM 3/1 ratio. The recommended ratios for this area after a vegetation mask has been applied are 5/7, 5/1, and a choice of 5/4, 7/4 or 5/2 to delineate hydrothermally altered rocks from unaltered rocks, as well as to distinguish among the unaltered lithologic units.

SPECTRAL MEASUREMENTS AND FIELD OBSERVATIONS

Spectral reflectance of rock and soil samples collected in the field area were measured in the laboratory on a Beckman UV 5240 spectrophotometer to verify spectral response in the TM image, to evaluate the band ratio selections, and to choose the enhancement methods used during preliminary processing. 105 spectral reflectance measurements were made of 75 samples of both hydrothermally altered and unaltered rocks, as well as several soils. The samples are representative of the various lithologies considered to be typical in the area and included rocks and soils from Cerros San Jeronimo, Antacahua, Huaricunca, Wila Kkollu, Cerke. Figures 3 and 4 show spectral reflectance curves for several altered and unaltered rocks in two of the larger anomalies, Cerro Wila Kkollu and Cerro San Jeronimo (Española deposit). The spectral data were convolved to TM band equivalent values by sampling each spectrum using the appropriate TM band filter response curves. From the resultant values the following TM equivalent ratios were calculated: 5/7, 3/1, 5/1, 5/4, 7/4, and 5/2. To evaluate the results, plots for several areas of interest were used to identify the optimum ratios for distinguishing altered rocks from unaltered rocks. (Figures 5 and 6)

Figures 7a-e show the distribution of potentially hydrothermally altered rocks in the five 1:50,000-scale quadrangles (Fig. 2) as visually interpreted from the TM color-ratio-composite images, and wherever feasible, corroborated by field work and spectral analysis. Five large anomalies in the study area correspond to very high reflectance values in TM ratios 5/4 and 3/1: 1) Cerro San Jeronimo (Española deposit) (Figure 7b); 2) Cerro Antacahua; (Figure 7a): 3) Cerros Huaricunca and Sinejavi (Figure 7c); 4) Cerro Wila Kkollu (Figure 7c); and 5) Cerro Cerke (Figure 7d). Cerros Antacahua, Huaricunca, Sinejavi, and Cerke are Miocene age volcanic centers, Wila Kkollu is a small stratavolcano or, perhaps, part of the Huaricunca volcanic complex, and San Jeronimo is primarily a volcanic dome complex. During field visits, samples were collected and analyzed for these five areas. Hydrothermal alteration with associated mineralization was confirmed for Cerros San Jeronimo, Antacahua, Huaricunca, and Wila Kkollu. The observations and spectral data from Cerro Cerke were less clear, and it is thought that the alteration was caused by fumarolic activity with no associated mineralization.

In addition to these five large areas numerous smaller scattered areas, which appeared as a less intense yellowish hue, in the CRC image, are present especially near the village of Berenguela and to the west. These areas are mapped with dashed lines on figures 7c and 7e. All these areas were not investigated in the field, but many are believed to be weakly hydrothermally altered; others are probably false anomalies caused by several reasons. Some small areas mapped near Cerro Pacokahua and just to the south of Pacokahua (Fig. 7e), consist of weakly altered rocks, perhaps related to emplacement of rhyolitic intrusive bodies. In addition, many small areas of Berenguela sandstones were mapped in this category. X-ray diffraction analysis revealed the presence of kaolinite, calcite, and jarosite.

The presence of jarosite indicates hydrothermal alteration due to sulfuric acid solutions (Mason and Berry, 1968). A few of the small anomalies consist of travertine deposits, which produce high TM 5/7 values. Thin sections of Berenguela sandstone formation were analyzed by R.F. Hardyman (in press) to confirm the presence of calcite and kaolinite in the matrix. The carbonate and clay matrix could produce relatively high values in TM 5/7 ratio, and the scattered areas figure 7c and 7e. Some areas consist of rocks that have been diagentically altered through normal weathering processes. These rocks can not be distinguished from hydrothermally altered due to their similar mineralogical compositions.

CONCLUSIONS

Areas of potentially hydrothermally altered rocks were mapped from the interpretation of TM satellite images. Two previously unmapped areas of hydrothermally altered rocks at Cerros Wila Kkollu and Antacahua were verified in the field and corroborated by spectral analysis. The mapped anomalies can be divided into two categories: 1) the TM ratio results show areas which are potentially intensely altered (solid line with tick marks) and 2) areas which are less intensively altered (dashed lines with tick marks). In the first category the largest area is located near Cerros Antacahua (Fig. 7a) and Sinejavi (Fig. 7c) and covers approximately 4,900m X 200m, whereas the other areas range in size down to as small as 800m X 200m. Areas in the second category mainly occur near the town of Berenguela and to the west of it. This area is dominated by the Berenguela redbed sandstones and Mauri arkoses with intrusive andesites. The CRC image with a vegetation mask allowed mapping of larger, more precise distribution of altered rocks in the Berenguela-Charaña areas than can the achieved using unmasked CRC images. Comparison of the original CRC images to the masked CRC images showed that masking greatly increases the amount of information available to the geologist. The original CRC image (TM 5/7, 3/1, 4/3) was dominated by the 3/1 ratio. This resulted in an image with large areas in green (3/1) and magenta (5/7, 3/1, 4/3) was dominated by the 3/1 ratio. This resulted in an image with large areas in green (3/1) and magenta (5/7 + 4/3) where vegetation dominated, and yellow where 5/7 and 3/1 values were very high, but with little other color variations. The combinations of ratios studied after the vegetation mask was applied, showed greater color variations among the rocks and soils related to lithologic differences.

Interpretation of Landsat TM images, particularly color-ratio-composite images, can assist in the evaluation of mineral potential, especially in remote areas with limited accessibility. The maps of potentially altered rocks can be combined with geologic, geochemical, and geophysical data to assess the potential mineral resources of an area. Differentiation of surface materials can be improved by applying a digital vegetation mask to the bands prior to additional enhancement. The recommended ratios for similar areas after a vegetation mask has been applied are 5/7, 5/1, and a choice of 5/4, 7/4, or 5/2 to distinguish hydrothermally altered rocks from unaltered rocks, as well as to distinguish regional lithologic differences. It should be noted that TM data of other, less vegetated areas in the Altiplano did not require a vegetation mask, and the use of vegetation mask should be evaluated on an area by area basis.

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Mason, B., and Berry, L.G., 1968, Elements of mineralogy: San Francisco, Calif., Freeman, W.H., 550 p.

Hardyman, R.F., in press, Reconaissance Geology of the Berenguela Region Southwest La Paz Department, Northwest Altiplano, Bolivia.

Figure 1 - Index map showing location of Landsat Thematic Mapper scenes and the four quarter scenes that were processed (rules and black area). The quarter scene that includes the Berenguela study area is shown in black.

Figure 2 - Index map showing the locations of 1:50,000-scale quadrangles, prominent topographic features, and the village of Berenguela.

Figure 3 - Visible and near-infrared reflectance spectra of hydrothermally altered rocks and unaltered dacite from the Wila Kkollu area.

Figure 4 - Visible and near-infrared reflectance spectra of hydrothermally altered and unaltered andesite from the San Jeronimo (Española) area.

Figure 5 - Plot showing the TM ratio response of hydrothermally altered and unaltered rocks from the Wila Kkollu area. The TM ratios were calculated from the laboratory spectra shown in figure 4.

Figure 6 - Plot showing the TM ratio response of hydrothermally altered and unaltered rocks from the Española area. The TM ratios were calculated from laboratory spectra shown in figure 5.

Figure 7 - Maps showing the distributions of intensely and weakly hydrothermally altered areas in five 1:50,000-scale quadrangles: (a) Antacahua; (b) Thola Kkollu; (c) Sinejavi; (d) Tambo Mauri: and (e) Berenguela.

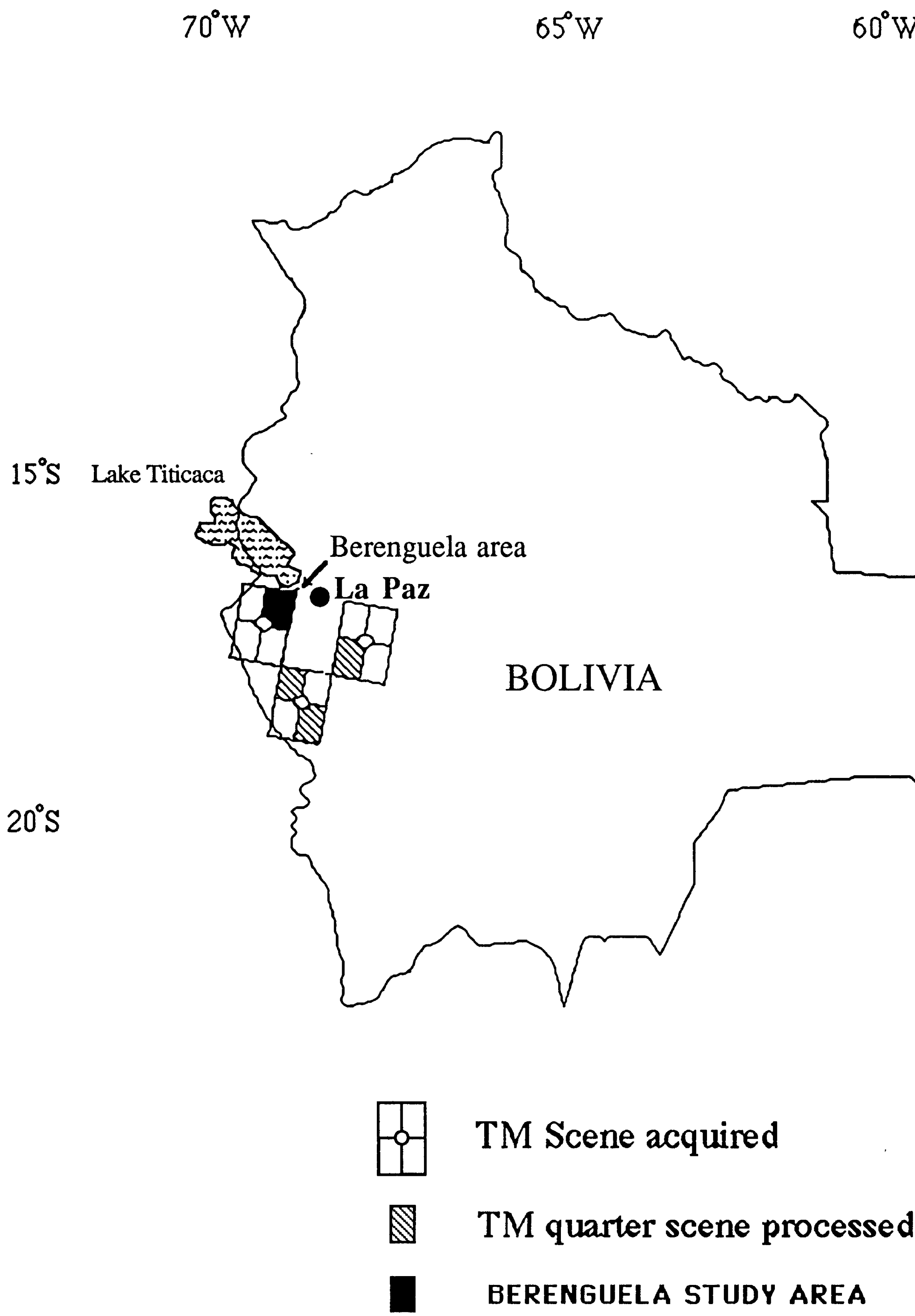
70°W
65°W
60°W
15°S
Lake Titicaca
Berenguela area
La Paz
BOLIVIA
20°S
TM Scene acquired
TM quarter scene processed
BERENGUELA STUDY AREA

Figure 1

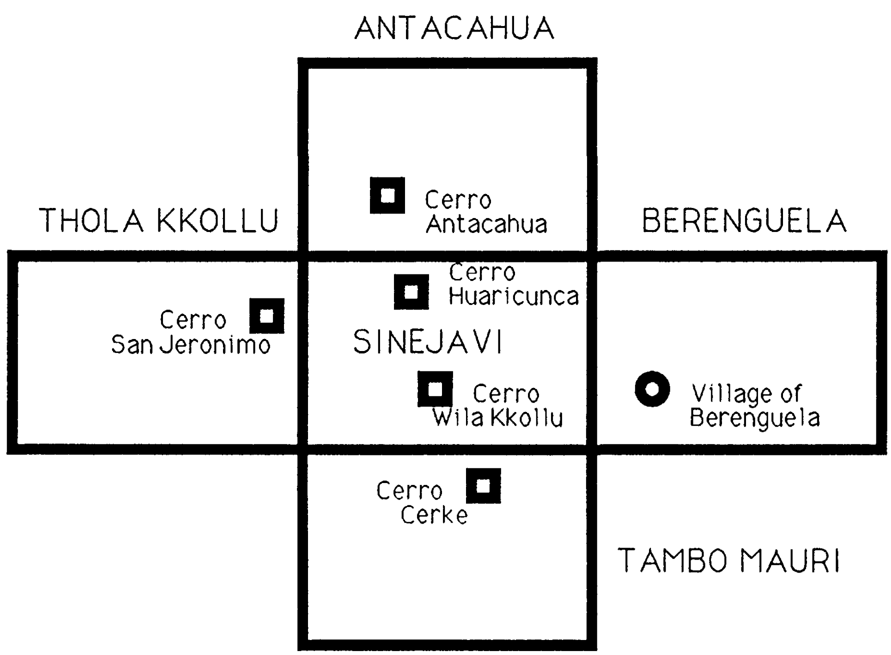
ANTACAHUA
Cerro Antacahua
THOLA KKOLLU
BERENGUELA
Cerro Huaricunca
Cerro San Jeronimo
SINEJAVI
Cerro Wila Kkollu
Village of Berenguela
Cerro Cerke
TAMBO MAURI

Figure 2

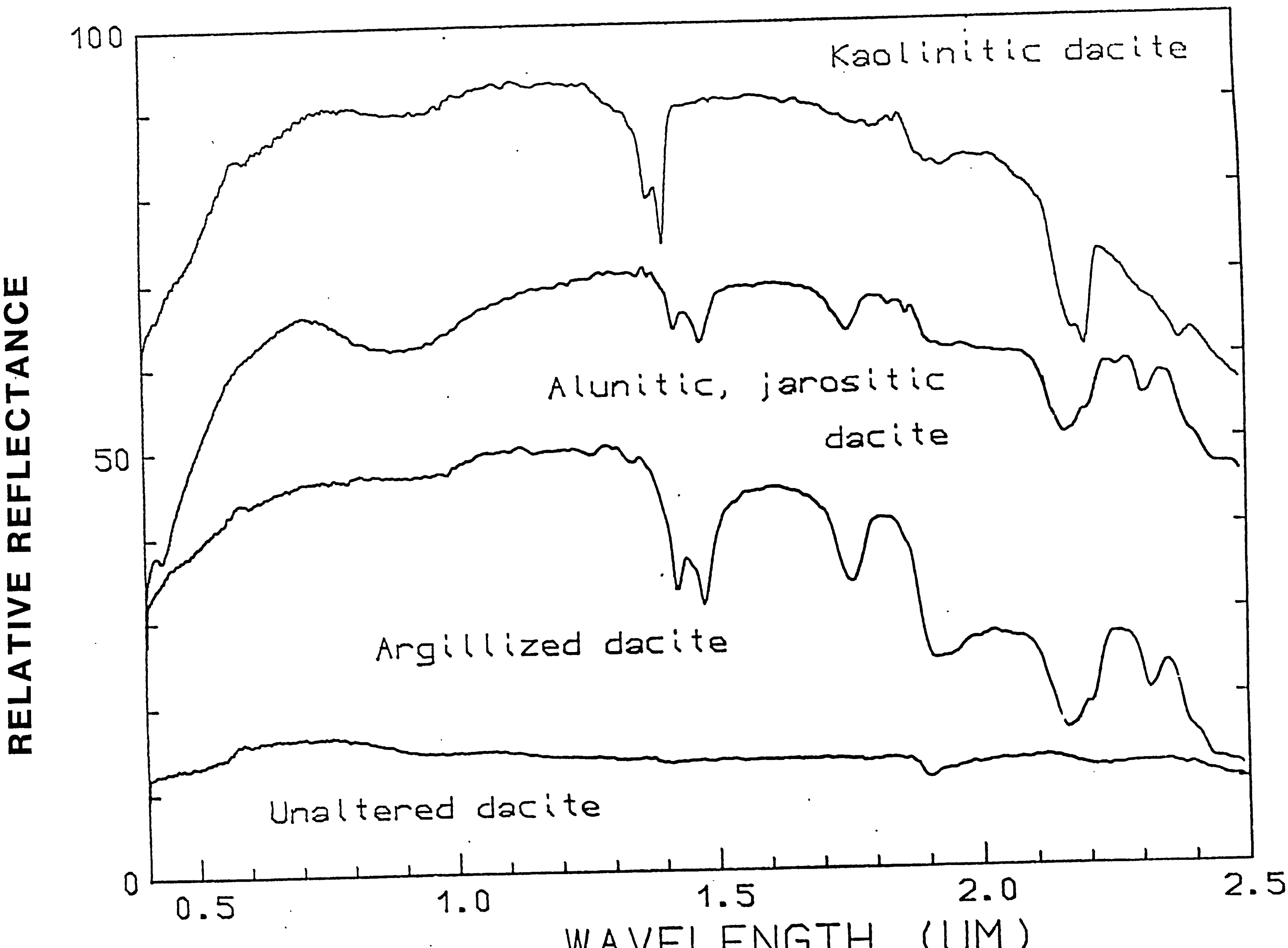

Figure 3

WILA KKOLLU

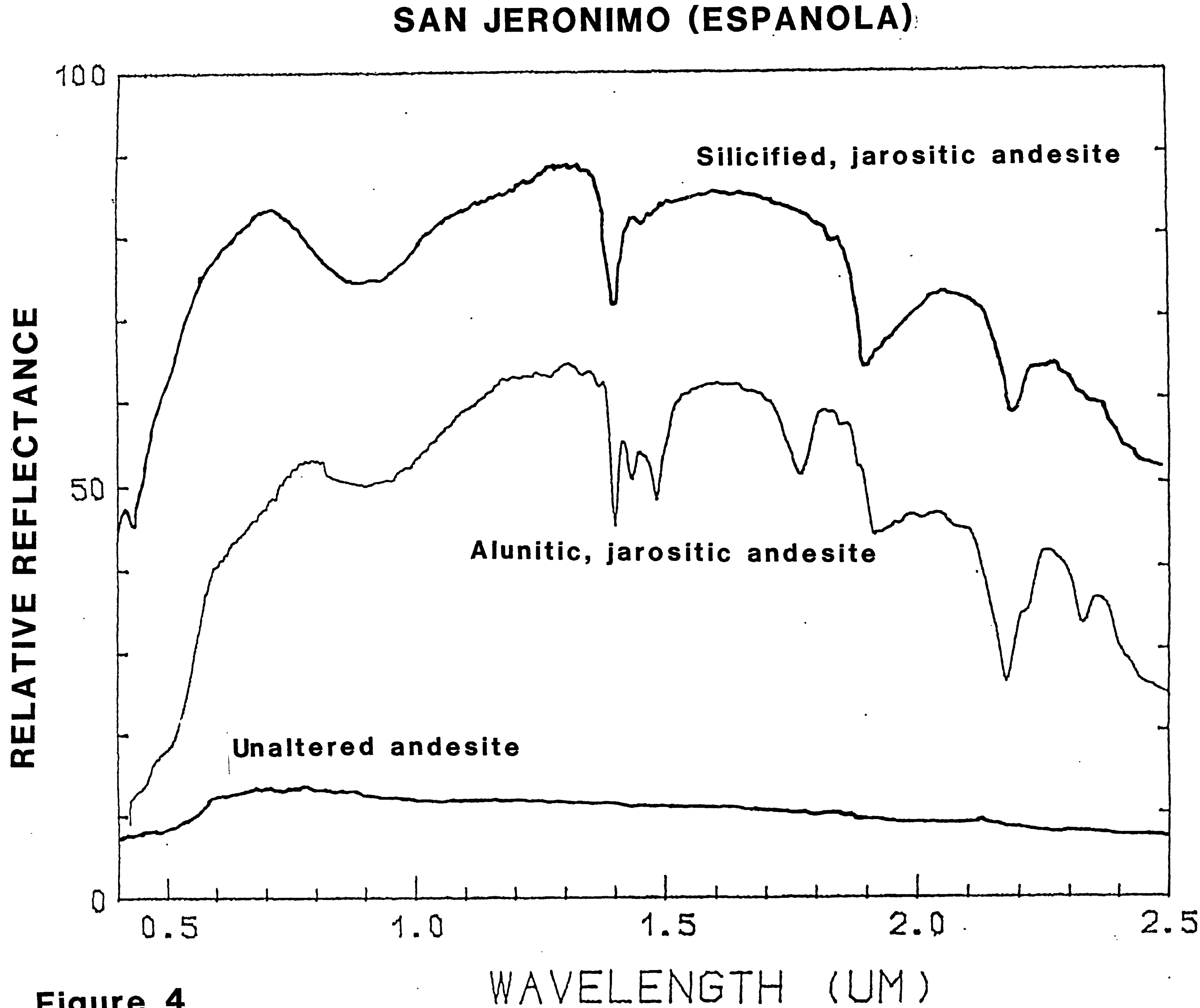
SAN JERONIMO (ESPANOLA)
Silicified, jarositic andesite
Alunitic, jarositic andesite
Unaltered andesite
RELATIVE REFLECTANCE
100
50
0
0.5
1.0
1.5
2.0
2.5
WAVELENGTH (UM)

Figure 4

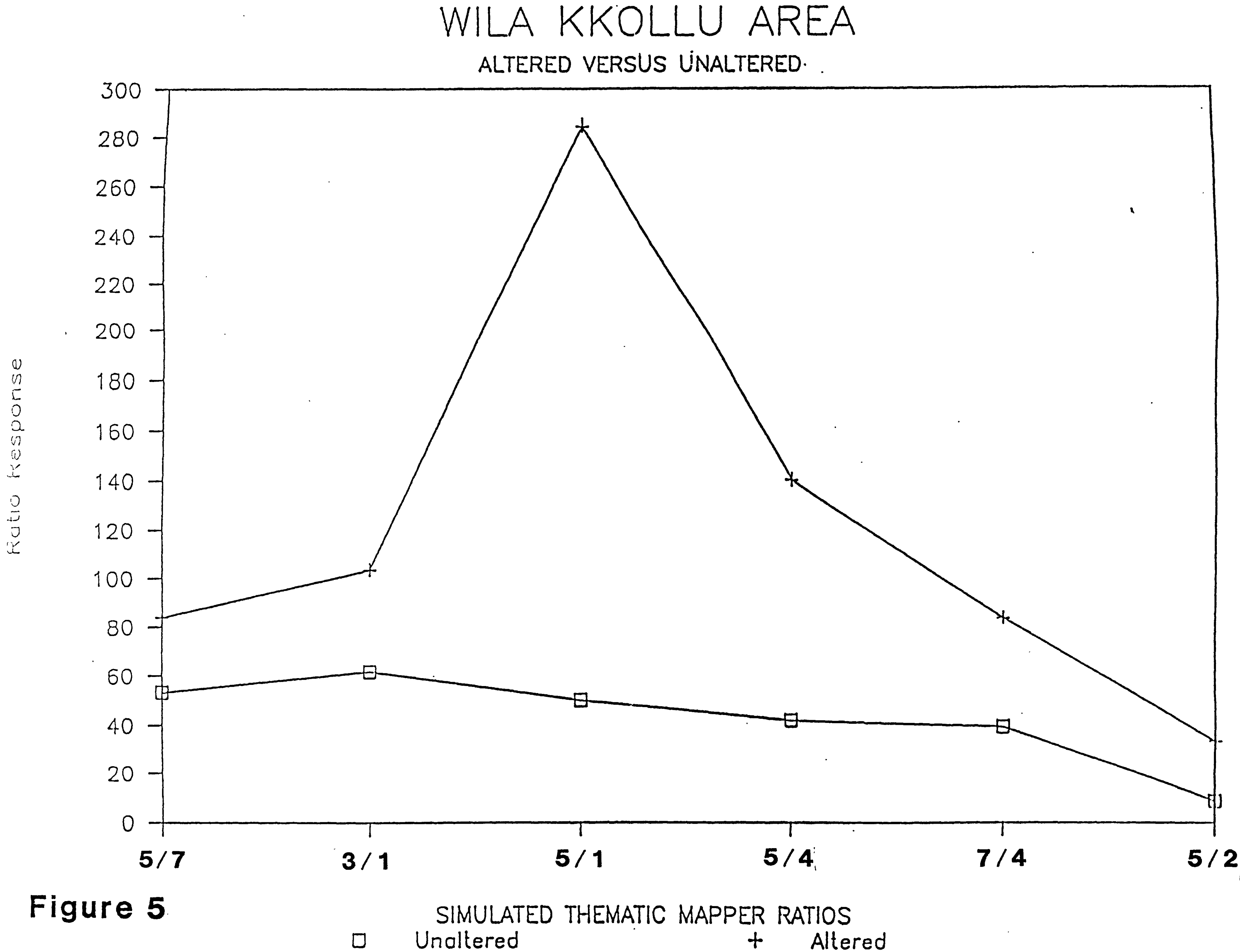
WILA KKOLLU AREA
ALTERED VERSUS UNALTERED
Ratio Response
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
5/7
3/1
5/1
5/4
7/4
5/2
SIMULATED THEMATIC MAPPER RATIOS
Unaltered
Altered

Figure 5

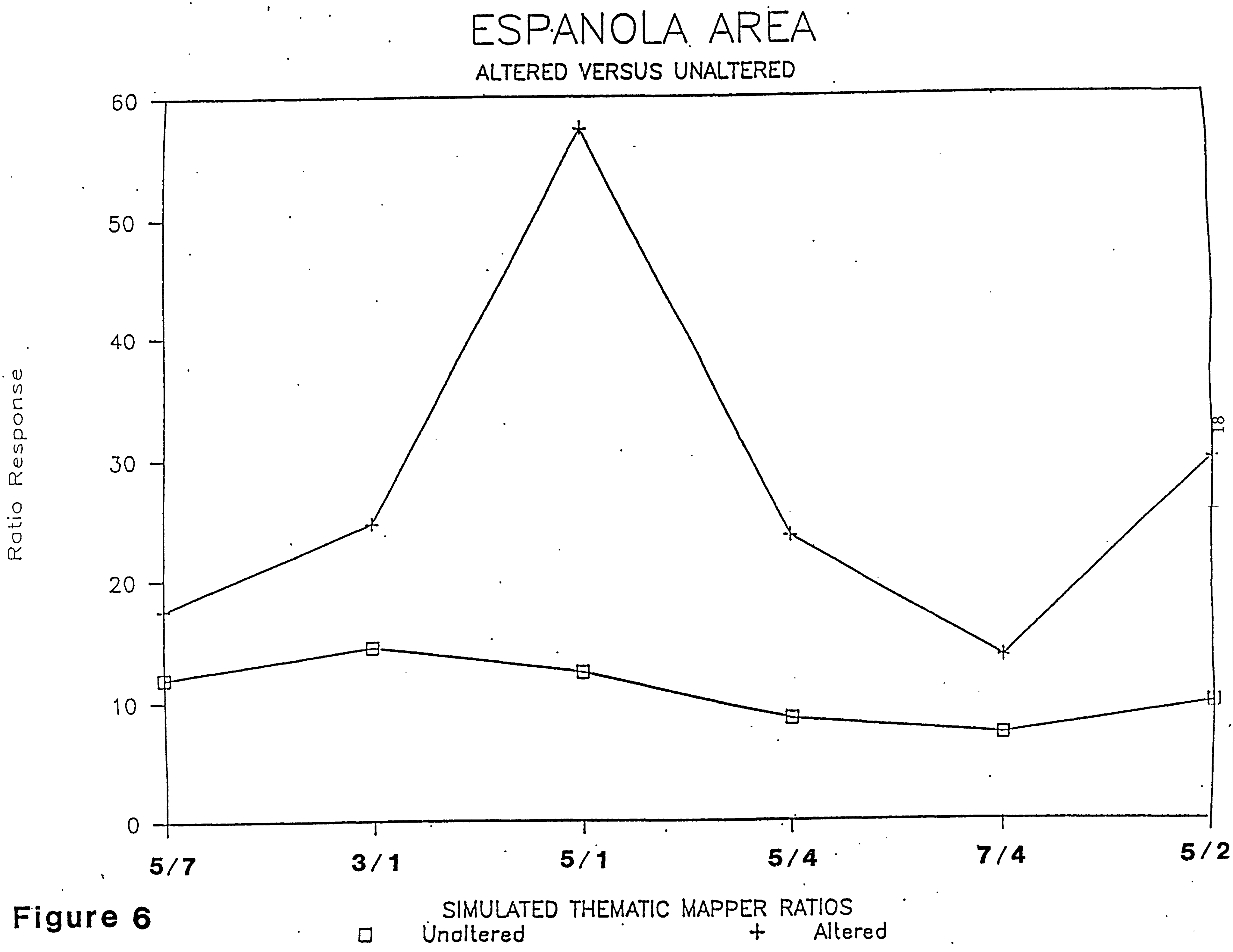
ESPANOLA AREA
ALTERED VERSUS UNALTERED
Ratio Response
60
50
40
30
20
10
0
5/7
3/1
5/1
5/4
7/4
5/2
SIMULATED THEMATIC MAPPER RATIOS
Unaltered
+ Altered

Figure 6