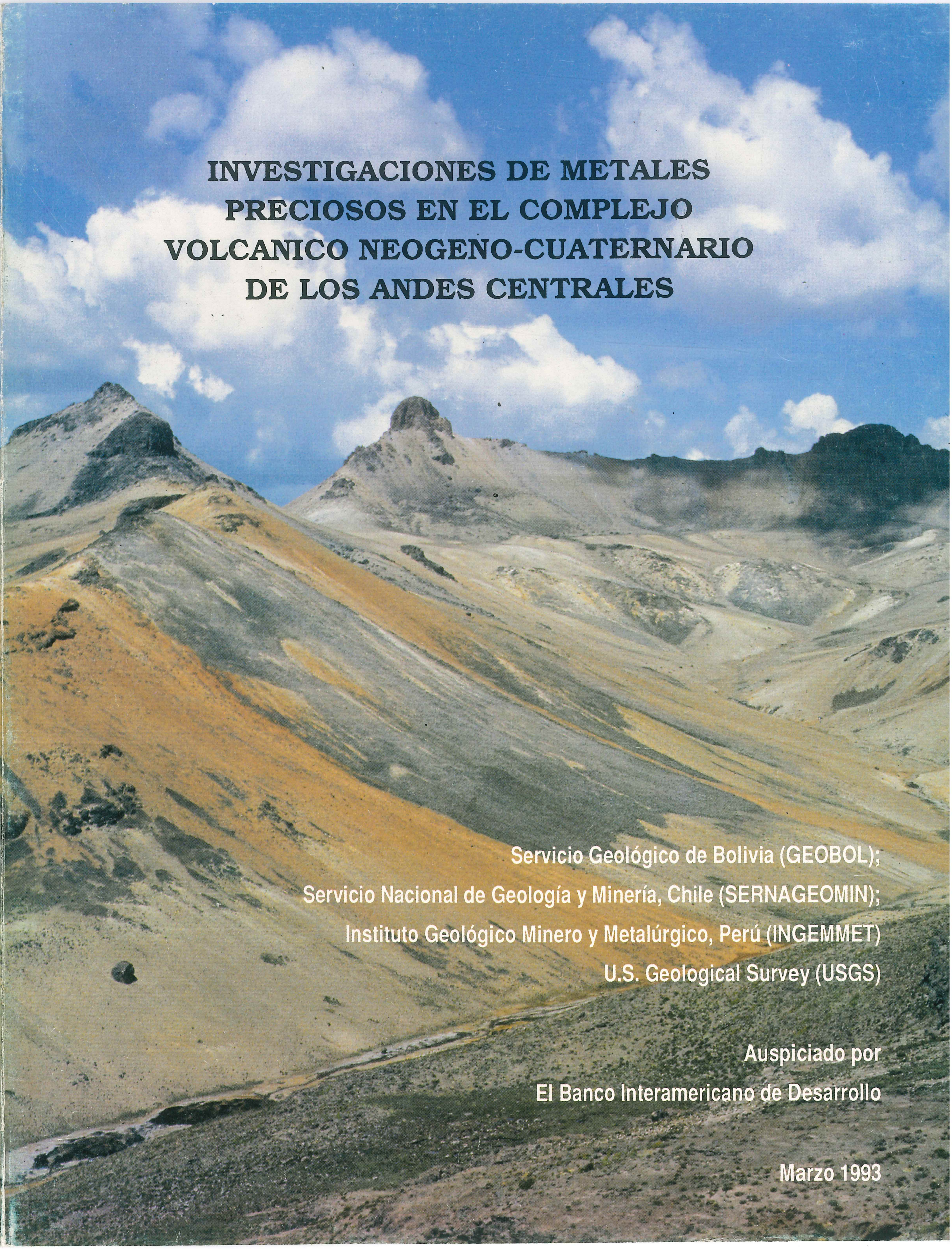
INVESTIGACIONES DE METALES PRECIOSOS EN EL COMPLEJO VOLCANICO NEOGENO-CUATERNARIO DE LOS ANDES CENTRALES



INVESTIGACIONES DE METALES PRECIOSOS EN EL COMPLEJO VOLCANICO NEOGENO-CUATERNARIO DE LOS ANDES CENTRALES

Servicio Geológico de Bolivia (GEOBOL);
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Instituto Geológico Minero y Metalúrgico, Perú (INGEMMET)
U.S. Geological Survey (USGS)

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CAPITULO II

ANALYSES OF LANDSAT THEMATIC MAPPER IMAGES OF STUDY AREAS LOCATED IN WESTERN BOLIVIA, NORTHERN CHILE, AND SOUTHERN PERU

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Investigación de metales preciosos en los Andes Centrales
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ABSTRACT

Landsat Thematic Mapper (TM) images were analyzed to identify volcanic and structural features and hydrothermally altered rocks in the Neogene-Quaternary volcanic field near Berenguela, western Bolivia, Esperanza, in the Maricurga district of northern Chile, and in the vicinity of the Orcopampa mine in southern Peru. These areas were being investigated for the presence of epithermal precious-metal deposits. Four TM image quadrants were processed for each country, and the resulting enhanced black-and-white single-band images, false-color composite (FCC) images, and color-ratio composite (CRC) images were printed at either 1:200,000- or 1:250,000-scale. In addition, a selected CRC image, which was designed for delineating hydrothermally altered rocks, was printed at 1:50,000-scale. A correction for atmospheric scattering was applied to most images, and snow and water were eliminated from the data using digital masking techniques.

Initial field evaluation of the 1:50,000-scale TM images of the Berenguela, Bolivia and Esperanza, Chile study areas indicated that the main areas of hydrothermally altered rocks were readily identified, but some important distinctions between altered and unaltered rocks, and subdivisions of these two broad groups, were not evident. Based on the field observations and subsequent spectral reflectance laboratory measurements of the main rock types, improved 1:50,000-scale CRC images were produced. For the Berenguela CRC image the most important modification to the initial TM 5/7, 3/1, 4/3 image was the application of a digital mask for vegetation, which covers 30 to 40 percent of the surface. Use of the vegetation mask permitted replacement of the TM 4/3 ratio, which is responsive to vegetation, with another ratio that provided improved lithologic discrimination. In addition, spectral reflectance studies showed that the TM 5/1 ratio was preferable to the TM 3/1 ratio for displaying Fe^{+3} absorption effects. The TM 5/7 ratio is sensitive to Al-OH absorption in alteration minerals, such as alunite and kaolinite, and Fe-OH absorption in jarosite. Five large areas consisting of hydrothermally altered rocks were delineated. Four of these areas are mineralized, and two areas had not been mapped previously. Also, numerous small scattered anomalous areas were delineated in the sandstone of Berenguela near the village of Berenguela. The presence of jarosite in some samples indicates that the sandstone contains, at least locally, the mineralized effects of hydrothermal alteration, but some of the CRC image anomalies may be caused by calcite and kaolinite related to diagenesis and/or weathering.

In the Esperanza study area interpretation of the TM 5/7, 5/1, and 5/4 1:50,000-scale CRC image was facilitated by producing a four-level pseudocolor density-sliced image of the TM 5/7 ratio and merging it with a black-and-white TM band 4 image. Analysis of reflectance spectra of samples collected within the four levels was used to determine the digital number boundaries. The results indicate that the density levels reflect differences in hydrothermal alteration intensity, which aided in elimination of false anomalies in the final map. Several previously unmapped areas consisting of hydrothermally altered rocks were identified.

The authors did not conduct field studies in southern Perú. However, the spatial distribution of probable hydrothermally altered rocks in the TM 5/7, 3/1, and 4/3 CRC image of the Orcopampa mine area is similar to that shown in an unpublished mine map, suggesting that the numerous anomalies shown on other parts of the Perú CRC image may also represent hydrothermally altered rocks.

INTRODUCTION

Landsat Thematic Mapper (TM) data have proven effective for mapping hydrothermally altered rocks in many arid and semi-arid areas (Rowan et al., in press; Podwysocki et al., 1985; Knepper and Simpson, 1992). This report discusses the application of TM data analysis to mapping hydrothermally altered rocks in the central Andes where epithermal volcanic-hosted deposits of precious-metal deposits are commonly associated with hydrothermal systems and have significant surface expressions. The objective of this study was to select the optimum TM band combinations and TM ratios to map potential areas of hydrothermally altered rocks and to facilitate regional geologic mapping.

In this report the data processing procedures and results of the analysis of TM images processed for study areas located in western Bolivia, northern Chile, and southern Peru are described. Individual reports prepared by scientists from these countries are contained elsewhere in this document and describe additional results of the TM data analysis.

OVERVIEW OF DATA AND DATA PROCESSING

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

BAND	WAVELENGTH (MICROMETERS)	
TM 1	0.45-0.52	(blue)
TM 2	0.52-0.60	(green)
TM 3	0.63-0.69	(red)
TM 4	0.76-0.90	(NIR)
TM 5	1.55-1.75	(NIR)
TM 6	10.3-12.5	(thermal)
TM 7	2.08-2.35	(NIR)

Four quarter scenes or image quadrants of Landsat TM digital data within each country were processed. Each quadrant covers approximately 8,100 square kilometers. Image products produced for each quadrant include: 1) a small-scale (1:200,000 or 1:250,000) black-and-white image of a single TM band for regional geologic structural analysis; 2) a small-scale false-color composite (FCC) of three bands for lithologic determinations; 3) a small-scale color-ratio composite (CRC) of three TM band ratios; and 4) a CRC image of a smaller area of interest at a map scale of 1:50,000. The CRC images were chosen to highlight hydrothermally altered rocks with potential associated mineralization.

Digital enhancement techniques used include: application of an atmospheric scattering correction, digital vegetation, water, and snow masks, a linear contrast stretch, and the production of TM band-ratio images. The TM sensor is designed to accommodate the highest and lowest anticipated radiance over all scenes, and therefore, any one particular scene uses only a small portion of the available dynamic response range. After examination of the frequency distribution of the data, high and low end points were selected to be stretched over the entire dynamic range of grey levels, between 0 and 255. Linear contrast stretching of the data greatly improves the contrast of the original brightness values. This permits easier and more accurate visual interpretation.

TM band ratios are created by dividing one TM band by another of the same area. When three ratios are combined they are assigned the colors of red, green, and blue to produce color-ratio-composite images. Ratio images accentuate spectral differences by minimizing brightness effects caused by topographic slope variations and albedo differences (Rowan et al., 1974).

Atmospheric scattering causes haze and low image contrast, and the correction technique 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, forces these pixels to a DN of 0 (black), thereby eliminating possible ambiguities. A vegetation mask was also used in processing the image of the Berenguela, Bolivia study area. The use of digital masks permitted improved enhancements of the spectral response of the rock and soil units by using more of the available dynamic range of gray levels.

BERENGUELA, BOLIVIA AREA

Geographic and geologic setting

The Berenguela, Bolivia study area is located East of the Bolivian Cordillera Occidental, in the highland plateau known as the Altiplano. The study area is situated 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 (Fig. 1). The area includes the village of Berenguela, and the following prominent peaks: Cerro Serkhe, Cerro Wila Kkollu, Cerro Huaricunca, Cerro Antacahua, and the Española deposit near Cerro San Gerónimo (Fig. 2). The study area encompasses approximately 1,400 sq. km. 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 dominate 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 but averages about 30 percent.

The Berenguela area consists of Neogene volcanic rocks and intrusive rocks, as well as Paleogene sedimentary units (personal communication, R.F. Hardyman). The region is dominated by andesitic-dacitic stratovolcanoes, volcanic domes, and ash-flow tuffs. According to Ericksen 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 Perú, western Bolivia, and northern Chile.

Image processing

During this study, four TM image quadrants were processed for the area located southwest of La Paz, Bolivia (Fig. 1). The main objectives were 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; and 4) field check the results of the TM image interpretation.

Image products produced for each quadrant include: a 1:250,000-scale black-and-white image of a single TM band for regional geologic structural analysis; a 1:250,000-scale FCC composite of TM bands 5, 4, and 1 for lithologic discrimination; a 1:250,000-scale CRC image of three TM band ratios; and a CRC image of the Berenguela area at

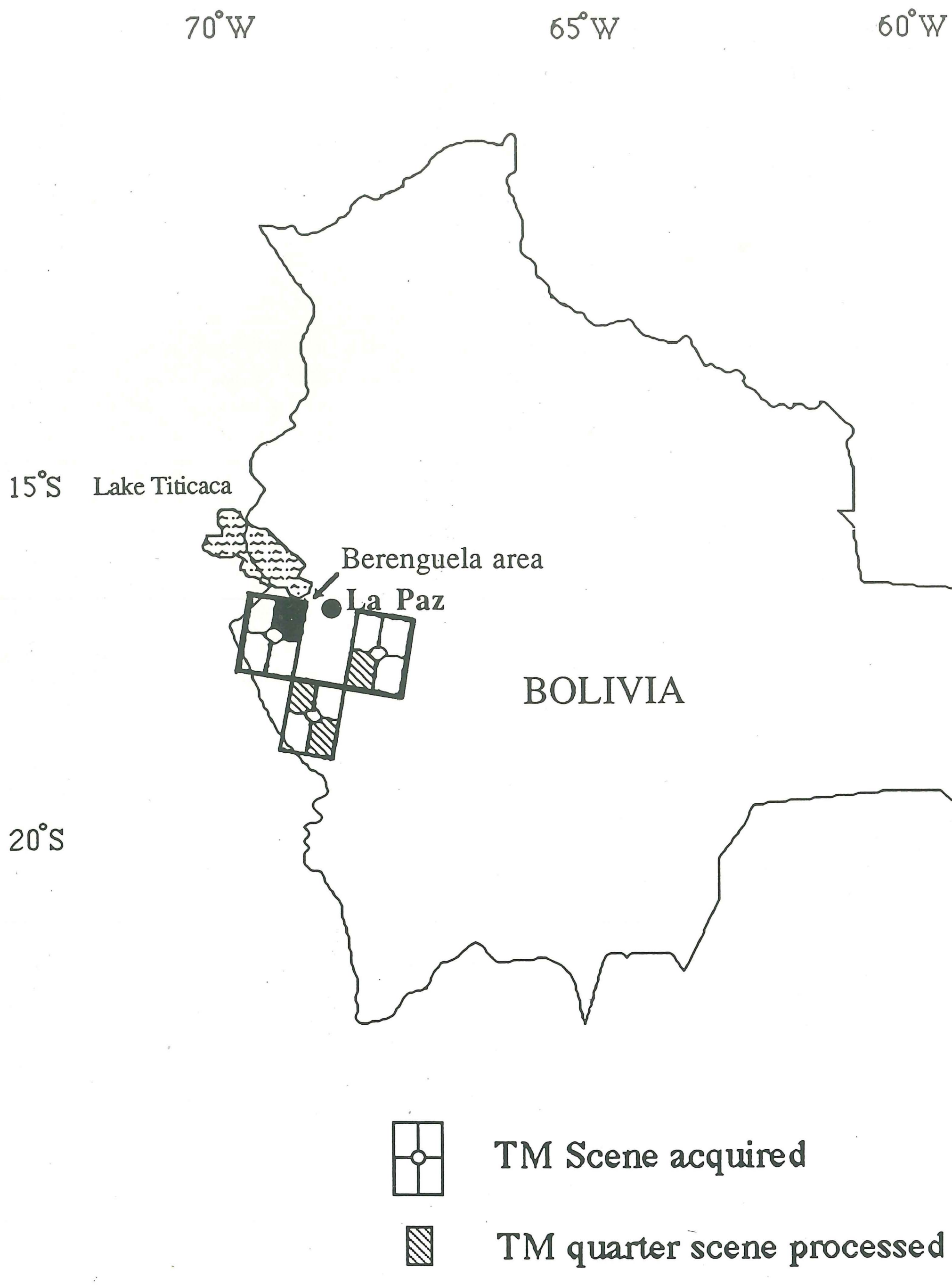

Figure 1.— *Index maps showing location of there Landsat Thematic Mapper scenes and the four image quadrants that were processed (ruled and black area). The image quadrant that includes the Berenguela study area is shown in black.*

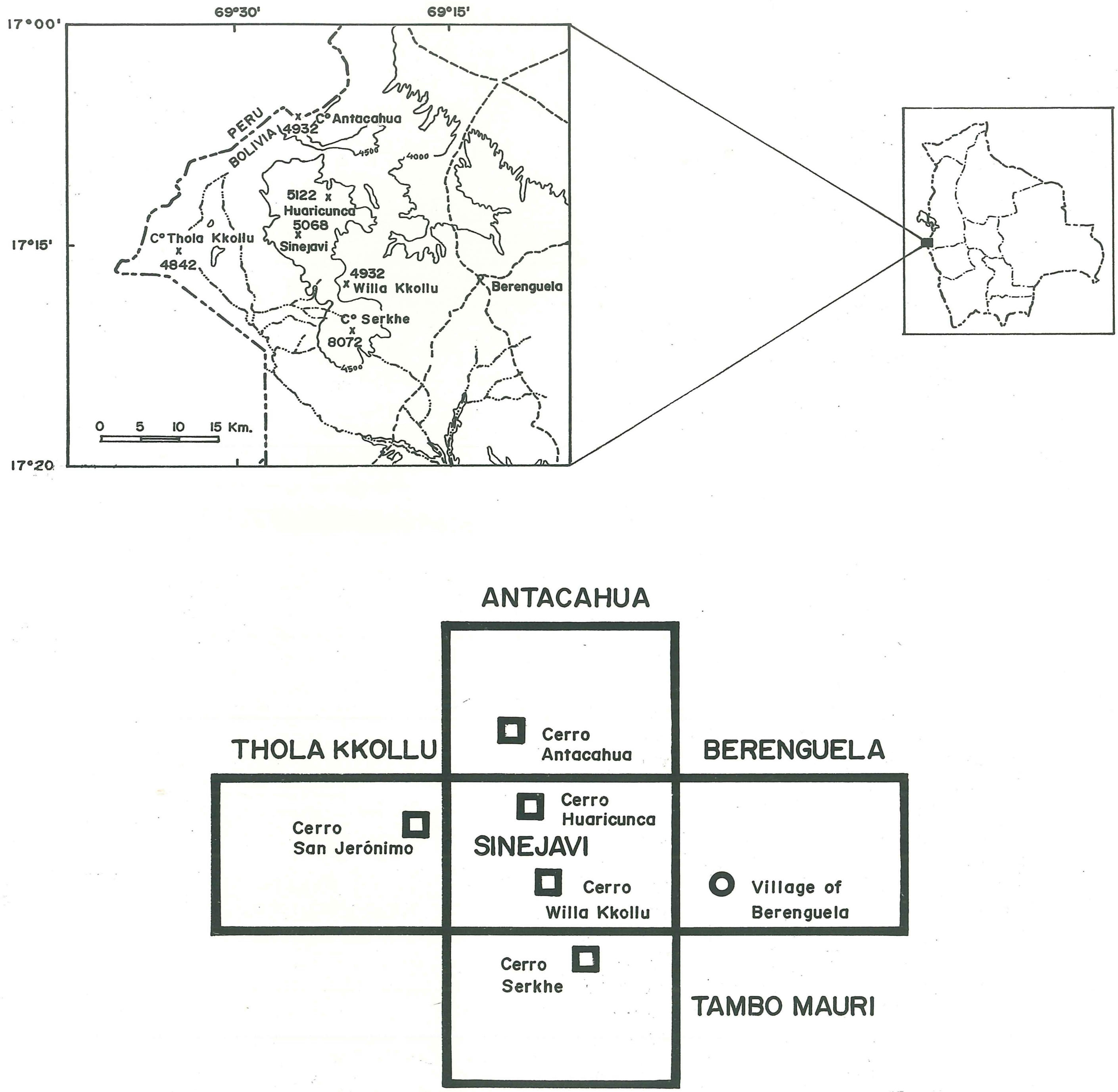

Figure 2.— *Index map showing the locations of 1:50,000-scale cuadrangles, prominent topographic features, and the village of Berenguela.*

1:50,000-scale. The digital TM data were processed using a Sun workstation and a PC system.

Quadrant two of the TM scene located at Path 002/ Row 072 (identification number Y5044014114XO) was selected for detailed analysis. Color-ratio-composite images using TM ratios 5/7, 3/1, and 4/3 displayed in red, green, and blue, respectively, were produced, printed to map scales, and evaluated in the field during 1990. TM ratio 5/7 shows spectral reflectance differences between rocks containing hydroxyl-bearing minerals and rocks that lack these minerals (Podwysocki et al., 1985). In figure 3, which shows field reflectance spectra of outcrops and vegetation in the western United States (Settle et al., 1984), note that the absorption feature located near 2.2 micrometers in the spectrum of an iron-and hydroxyl-bearing rock is not present in the andesite and sandstone spectra. This feature may be caused by Al-OH minerals, such as kaolinite and muscovite, which have strong and distinct absorption features centered near 2.2 micrometers (TM band 7) (Hunt, 1977). Carbonate minerals and Mg-OH-bearing minerals also have strong absorption features between 2.30 and 2.35 micrometers (carbonate-bearing rock, Fig. 3). Rocks and soils containing clays, micas, sulfate minerals (alunite, jarosite), and carbonate minerals have high DN values in TM 5 relative to TM 7 values and, therefore, result in high TM ratio 5/7 values. It should be noted, however, that 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 in TM 7 than TM 5 (Fig. 3). To distinguish vegetation from other surface materials, TM ratio 4/3 was included in the CRC images. In the TM 4/3 ratio, 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 in the near-infrared between 0.80 and 1.30 micrometers (TM 4 region) due to scattering by leaf cell structures. Most rocks and soils have low spectral contrast in the TM 4/3 ratio (Fig. 3), 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-bearing minerals produce diagnostic spectral features in the visible range of the electromagnetic spectrum, which result in decreasing reflectance toward shorter wavelengths (iron - and hydroxyl-bearing rock, Fig. 3). Therefore, limonitic areas yield higher DN values in TM ratio 3/1 than nonlimonitic areas yield.

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 TM ratio 4/3 values (blue), and appear yellow (red + green) in the CRC images.

TM color-ratio composite images 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. Because vegetation yields a high response in TM 5/7, 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 authors concluded that discrimination of the altered rocks 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 composite (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 appear red in the CIR 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 ambiguities between altered areas and vegetated areas were greatly reduced. For a subset of the Berenguela TM scene, a vegetation mask was applied to the individual bands and, subsequently, ratios were created.

Applying the vegetation mask did improve 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

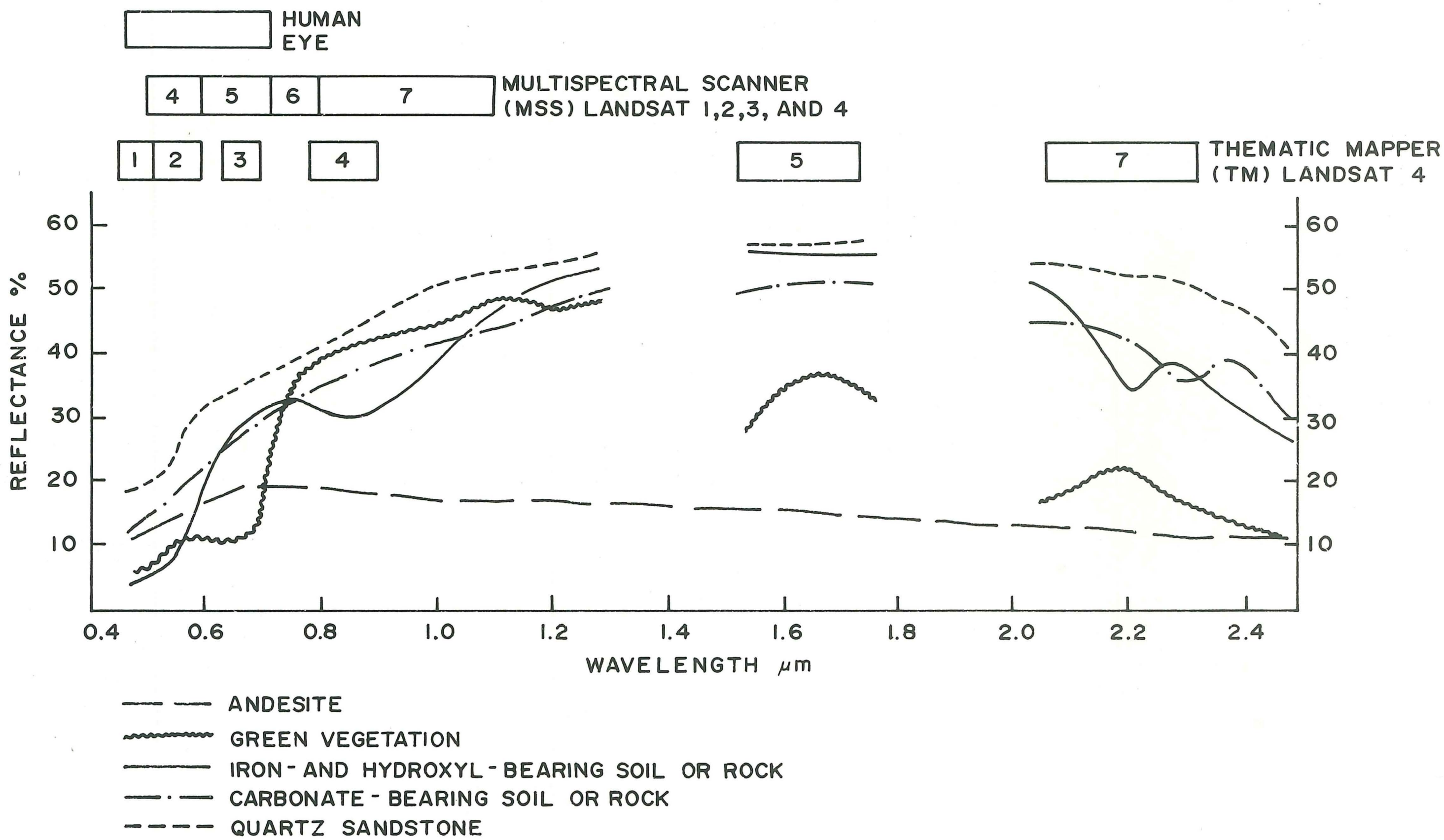

Figure 3.— *Typical visible and near-infrared in situ reflectance spectra recorded in the western United States for three unaltered rocks, a hydrothermally altered rock, and vegetation (Settle et. al., 1984). Location of landsat TM bands are shown at top. Gaps in spectra in the 1.4 and 1.9 micrometers region are caused by strong atmospheric absorption.*

allowed us to eliminate TM ratio 4/3, and we included another ratio in the final color-ratio-composite image. This ratio contains spectral information that improved separation among unaltered rock types and facilitated distinguishing compositionally different hydrothermally altered rocks.

Spectral reflectance measurements of field samples were convolved to the TM bandpasses, and equivalent TM ratio values were calculated for the main rock types to assist in the selection of the optimum ratios. 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 was measured in the laboratory using a Beckman UV 5240* spectrophotometer equipped with an integrating sphere to verify spectral responses displayed in the TM image and to evaluate the band ratio selections and 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 soil samples.

The samples are representative of the various lithologies considered to be typical in the area and included rocks and soils from Cerros San Gerónimo, Antacahua, Huaricunca, Wila Kkollu, and Serkhe. Figures 4 and 5 show spectral reflectance curves for several altered and unaltered rocks in two of the large anomalies, Cerro Wila Kkollu and Cerro San Gerónimo (Española deposit). The spectral data were convolved to 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. 6 and 7). In figures 6 and 7 note that the difference between the altered and unaltered rocks is substantially larger for the TM 5/1 than the TM 3/1 ratio.

Discussion

Figures 8a-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, where feasible, corroborated by field work and spectral analysis. Five large anomalies in the study area correspond to very high values in TM ratios 5/7 and 3/1: 1) Cerro San Gerónimo (Española deposit) (Fig. 8b); 2) Cerro Antacahua (Fig. 8a); 3) Cerros Huaricunca and Sinejavi (Fig. 8c); 4) Cerro Wila Kkollu (Fig. 8c); and 5) Cerro Serkhe (Fig. 8d). Cerros Antacahua, Huaricunca, Sinejavi, and Serkhe are Miocene age volcanic centers, Wila Kkollu is a small stratovolcano or, perhaps, part of the Huaricunca volcanic complex, and San Gerónimo is primarily a volcanic dome complex. Of the five areas mapped as potentially hydrothermally altered, the Cerro Antacahua (Fig. 8a) and Cerros Sinejavi and Huaricanca (Fig. 8c) areas have not been mapped previously and proved upon field investigation to be altered and mineralized. Hydrothermal alteration with associated mineralization was also confirmed for Cerros San Gerónimo and Wila Kkollu. The observations and spectral data from Cerro Serkhe 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 of the village. These areas are mapped with dashed lines on figures 8c and 8e. 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 consist of weakly altered rocks, perhaps related to emplacement of rhyolitic intrusive bodies. In addition, many small areas were mapped in this category within the sandstone

* Any use of trade, product or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

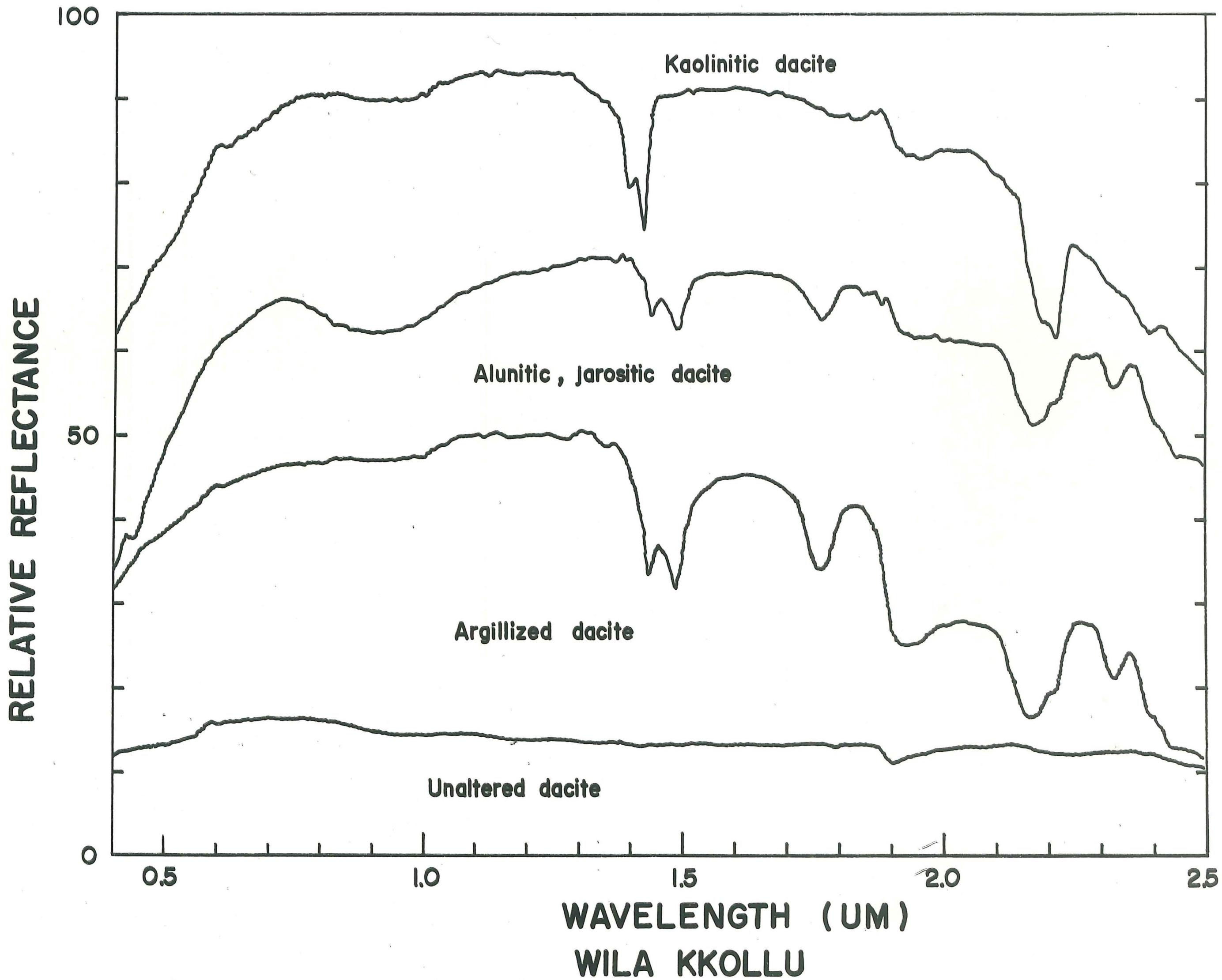

Figure 4.— *Visible and near-infrared reflectance spectra of hydrothermally altered rocks and unaltered dacite from the Wila Kkollu area.*

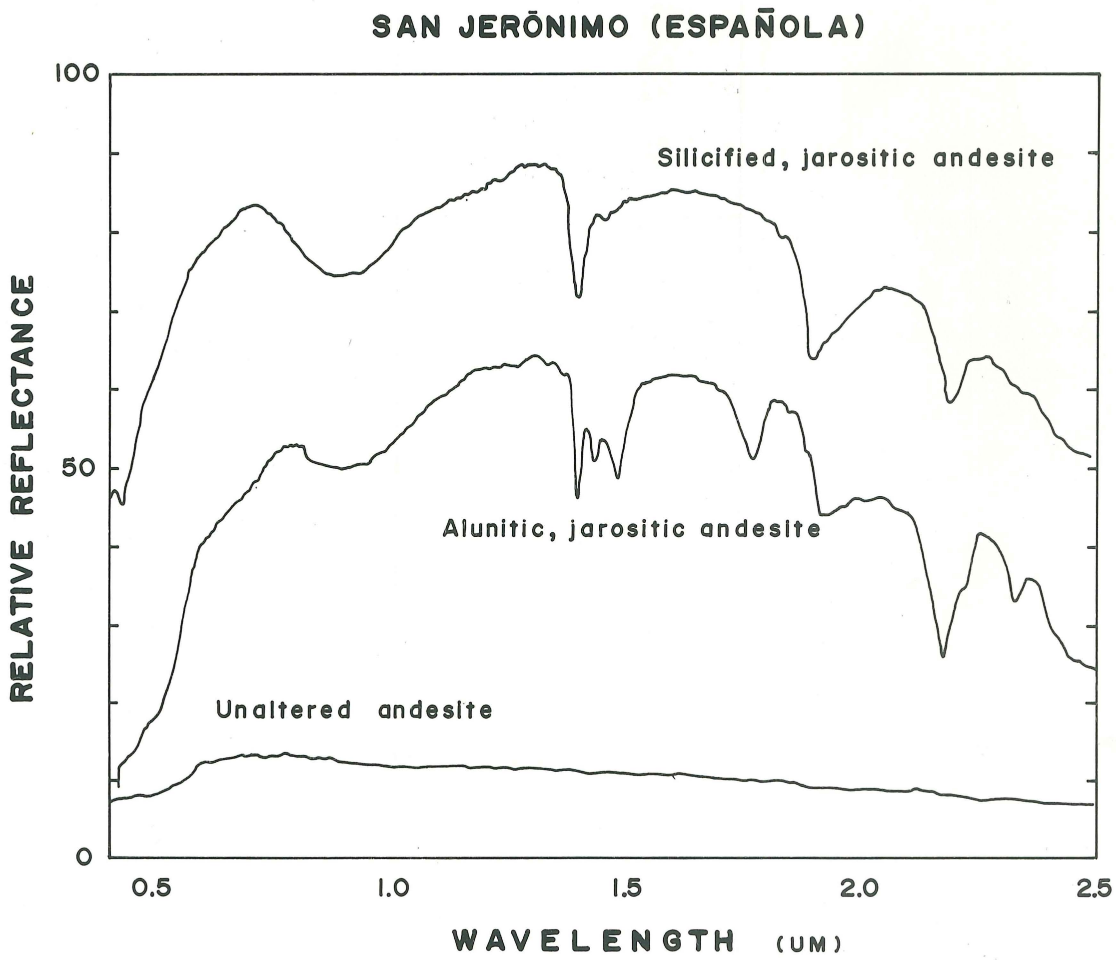

Figure 5.— Visible and near-infrared reflectance spectra of hydrotermally altered and unaltered andesite from the San Gerónimo (Española) area.

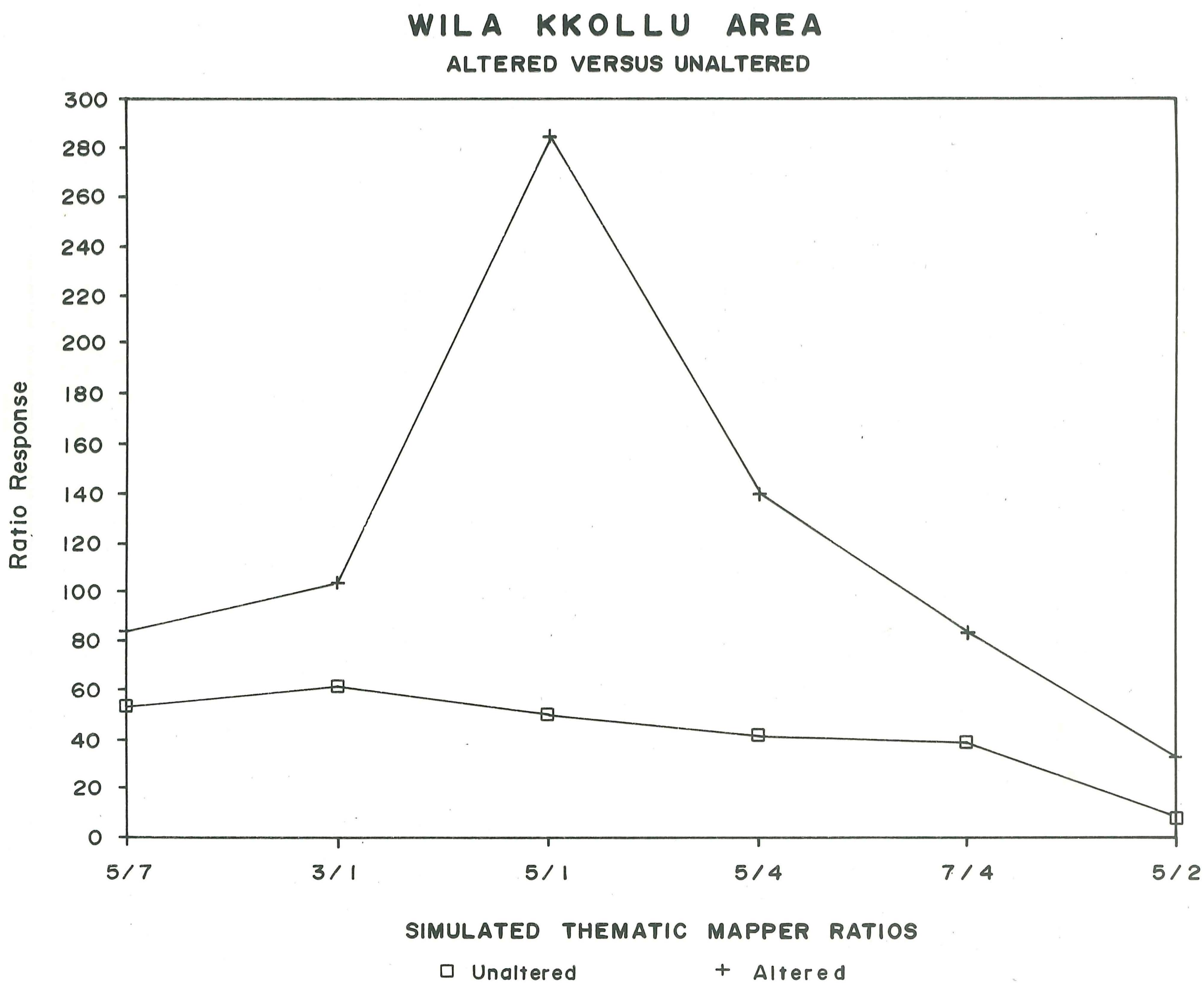

Figure 6.— *Plot showing the TM ratio response of hydrothermally altered and unaltered rocks from the Wila Kkollu area. The TM ratios were calculated from the laboratory spectra shown in figure 4.*

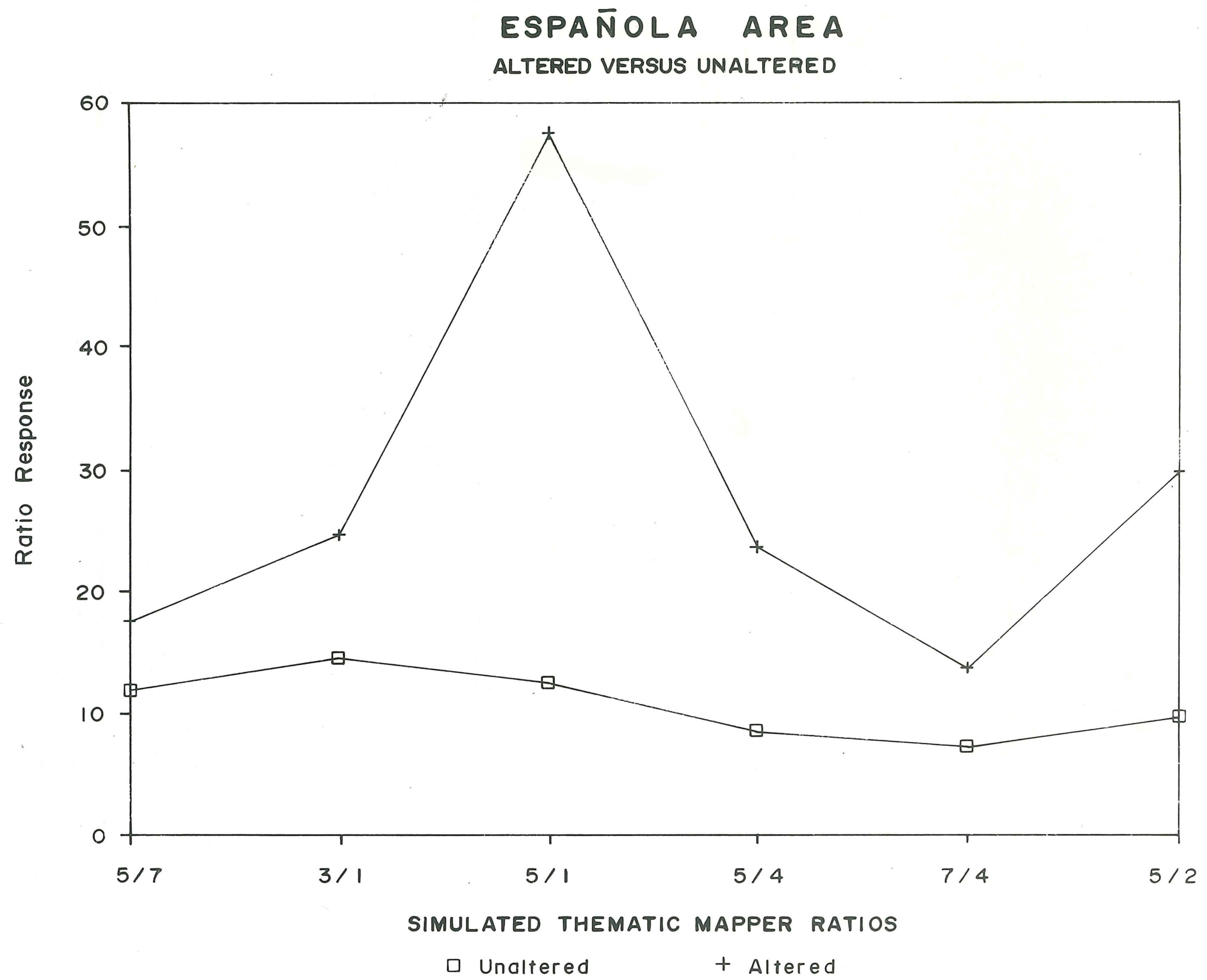

Figure 7.— *Plot showing the TM ratio response of hydrothermally altered and unaltered rocks from the Española area. The TM ratios were calculated from laboratory spectra shown in figure 5.*

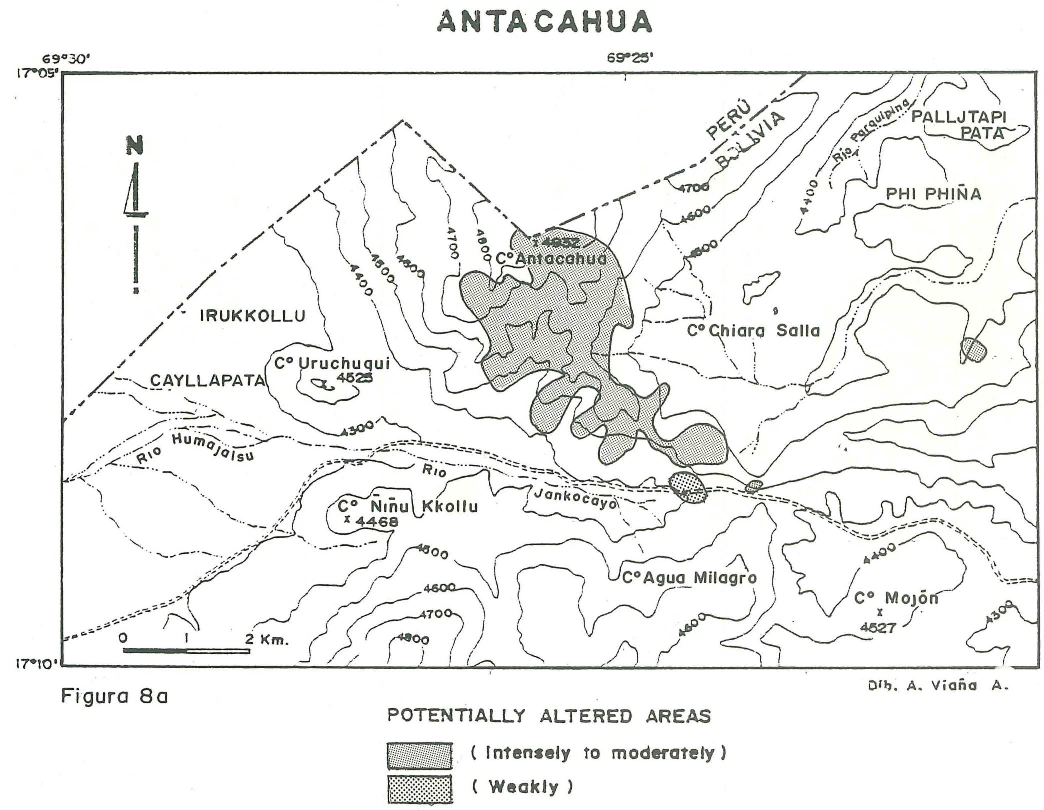

Figure 8a.— Maps showing the distributions of intensely and weakly hydrothermally altered areas in five 1:50,000-scale quadrangles: (a) Antacahua; (b) Thola Kkollu; (c) Sinejavi; (d) Tambo Mauri; and (e) Berenguela.

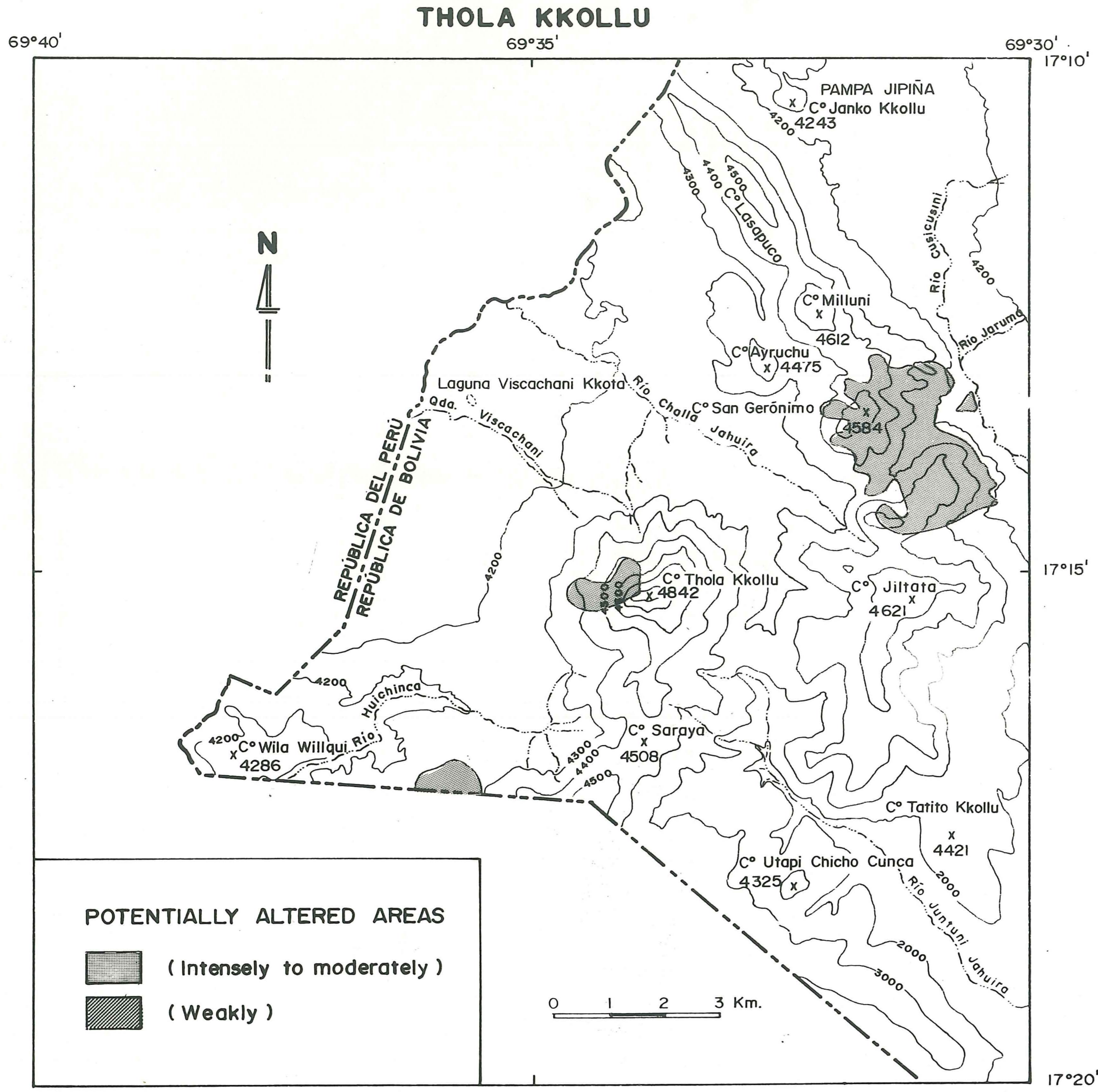
THOLA KKOLLU
69°40'
69°35'
69°30'
17°10'
17°15'
17°20'
N
PAMPA JIPIÑA
C° Janko Kkollu
4243
C° Lasapuco
C° Milluni
4612
C° Ayruchu
4475
C° San Gerónimo
4584
Laguna Viscachani Kkota
Qda. Viscachani
Río Challa Jahuira
Río Cusicusini
Río Jarumo
REPÚBLICA DEL PERÚ
REPÚBLICA DE BOLIVIA
C° Thola Kkollu
4842
C° Jiltata
4621
Huichinca
C° Wila Willqui
4286
Río
C° Saraya
4508
C° Tatito Kkollu
4421
C° Utapi Chicho Cunca
4325
Río Juntuni Jahuira
POTENTIALLY ALTERED AREAS
(Intensely to moderately)
(Weakly)
0 1 2 3 Km.

Figure 8b.—

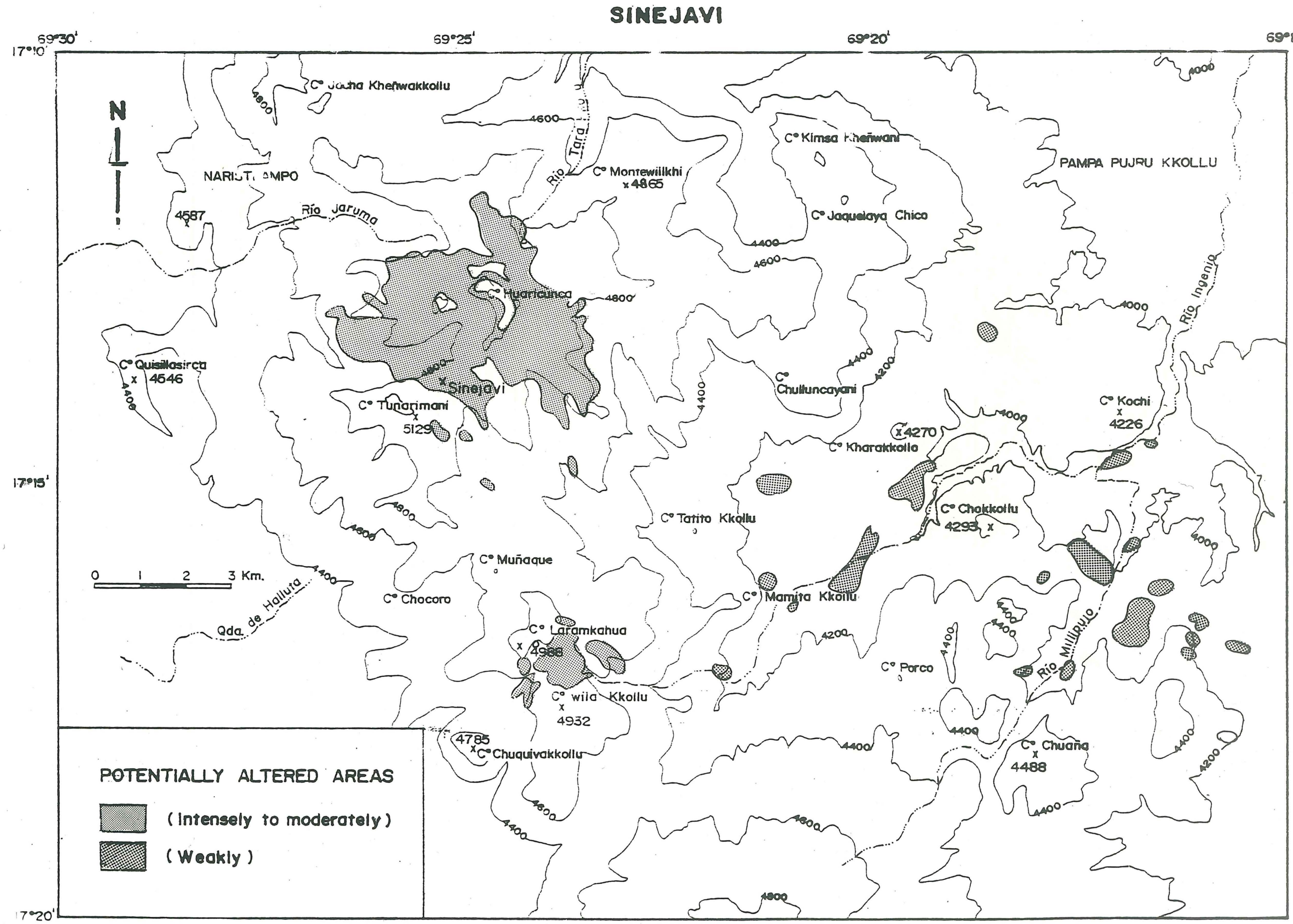
SINEJAVI
69°30'
69°25'
69°20'
69°15'
17°10'
17°15'
17°20'
N
C° Kimsa Kheñwani
PAMPA PUJRU KKOLLU
NARISTI AMPO
Río Jaruma
C° Montewillkhi
x 4865
C° Jaquelaya Chico
4587
C° Huariaunca
Río Ingenio
C° Quisillasirca
x 4546
x Sinejavi
C° Tunarimani
5129
C° Chulluncayani
x 4270
C° Kharakkolla
C° Kochi
4226
C° Chokkollu
4293
C° Tatito Kkollu
0 1 2 3 Km.
C° Muñaque
C° Chocoro
Qda. de Halluta
C° Mamita Kkollu
C° Laramkahua
4988
C° wila Kkollu
4932
C° Porco
Río Millipujo
4785
C° Chuquivakkollu
C° Chuaña
4488
POTENTIALLY ALTERED AREAS
(Intensely to moderately)
(Weakly)

Figure 8c.—

TAMBO MAURI

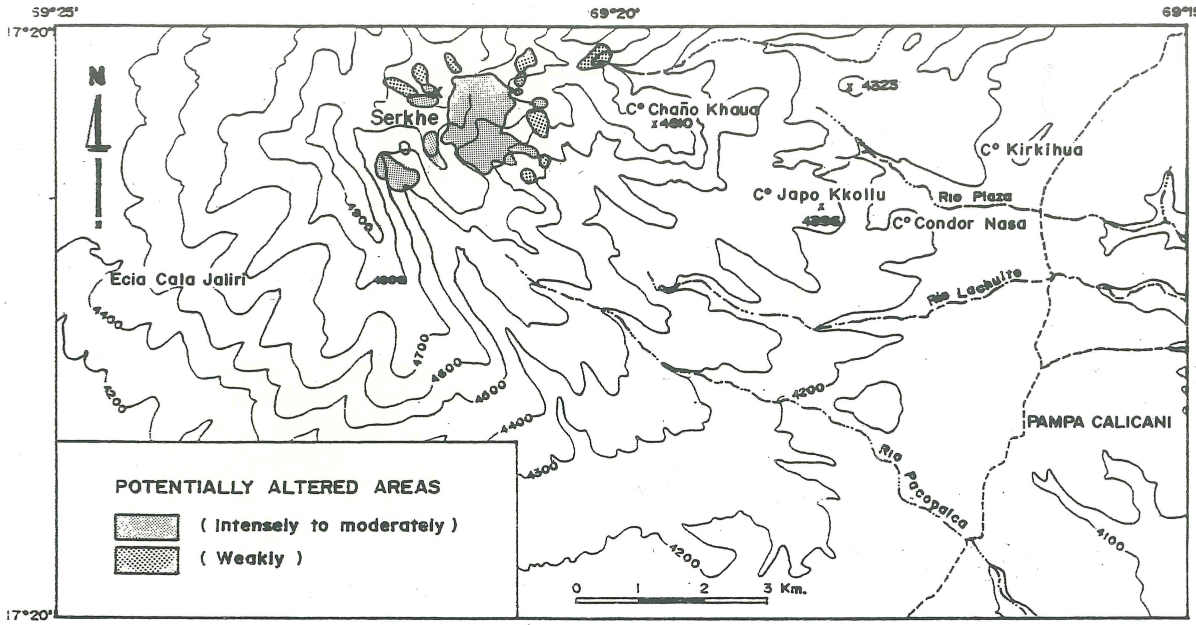

Figure 8d.—

BERENGUELA

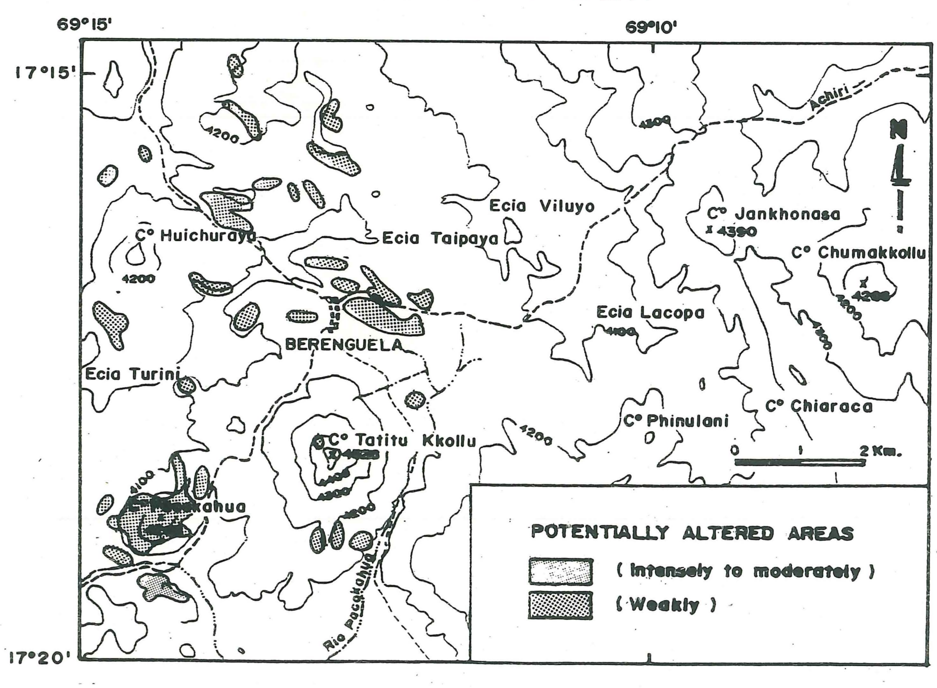

Figure 8e.—

of Berenguela. X-ray diffraction analysis of samples collected from the sandstone revealed the presence of kaolinite, calcite, and jarosite, and thin section analysis of the sandstone by R.F. Hardyman confirmed the presence of calcite and kaolinite in the matrix. The carbonate and clay matrix, which may be either related to hydrothermal alteration or diagenisis, could produce relatively high values in TM 5/7 ratio and the scattered areas on figures 8c and 8e. However, the presence of jarosite indicates hydrothermal alteration due to sulfuric acid solutions (Mason and Berry, 1968), which suggest that the sandstone is at least locally altered. A few of the small anomalies consist of travertine deposits, which produce high TM 5/7 values. Some areas may consist of rocks that have been diagentically altered through normal weathering processes. These rocks can not be distinguished from hydrothermally altered rocks due to their similar mineralogical compositions.

Summary, Berenguela study area

The CRC image with a vegetation mask allowed mapping of larger, more precise distributions of altered rocks in the Berenguela area than can be 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), 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 larger 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 TM 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 a vegetation mask should be evaluated on a case by case basis.

ESPERANZA, CHILE AREA

Landsat Thematic Mapper (TM) images were analyzed to augment conventional methods for investigating volcanic-hosted epithermal precious and semi-precious metal deposits in the Neogene-Quaternary volcanic complexes in northern Chile. TM data were digitally processed and enhanced to distinguish lithologic units and to map hydrothermally altered rocks (Fig. 9). 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 improved image enhancement.

The objectives of this study were to 1) map hydrothermally altered rocks at a scale of 1:50,000; 2) investigate the spectral properties of epithermal volcanic and sedimentary rocks and 3) field check the results of the TM image interpretation.

After the 1990 field investigations were carried out in the Esperanza area, spectral measurements of representative samples were analyzed to identify and verify the spectral responses displayed in the TM images. It was determined that more information could be extracted from the TM data of this area when the potentially altered areas were processed separately from the predominately fresh volcanic and sedimentary rocks. Hydrothermally altered rocks were digitally separated from the unaltered rocks, and subsequent processing of the two distinct areas improved the information content of the images.

Geographic and geologic setting

The Esperanza area is located in northern Chile approximately 73 kilometers northeast of the town of Copiapó in the Region of Atacama (Fig. 9). Northern Chile is dominated by a range of Neogene andesitic-dacitic stratovolcanos which overlie an upper Paleozoic sedimentary basement composed of sandstone, conglomerate, and shale (unpublished map, 1984, J. Muñoz). North of the study area the basement rocks are intruded by Permian-Triassic granitoids of the Perdernales batholith. According to Ericksen et al., (1987), epithermal volcanic-hosted gold-silver deposits are associated with Neogene-Quaternary volcanic centers in northern Chile, and many had prominent hydrothermal alteration systems.

The area covered by the TM images transects portions of three 1:50,000-scale topographic sheets listed from west to east: Cerros Bravos; Pastos Largos; and Rio Juncalito. Elevations range from approximately 3,700 m to slightly above 5,300 m above sea level. The study site is located just south of the Atacama desert, known to be the driest desert in the world. A few of the ephemeral streams in the area support sparse desert vegetation in the valleys, but most of the area lacks significant vegetation cover.

Description of data

The digital image data were collected by the Landsat-5 Thematic Mapper sensor on March 15, 1985. The four image quadrants that were processed are shown in figure 9. Each image quadrant covers approximately 8,100 sq. km. Image products produced for each quadrant include: a 1:250,000-scale black-and-white image of a single TM band for regional geologic structure analysis; a 1:250,000-scale FCC image of TM bands 5,4, and 3 for lithologic determinations; a 1:250,000-scale CRC image of three TM band ratios and a 1:50,000-scale CRC image of the Esperanza study area. The CRC image was designed to highlight potentially hydrothermally altered rocks. The digital data collected by the Thematic Mapper sensor on the Landsat-5 satellite, were processed using a Sun workstation and a PC system. Quadrant three of the TM scene located at Path 233/ Row 078 (identification number Y5037814020XO) was digitally enhanced and printed at 1:50,000-scale prior to visiting the field area in 1990 and 1991.

Image processing techniques

The main objective of the image processing for the Esperanza area was to facilitate delineation of hydrothermally altered rocks. Digital enhancement techniques included application of linear contrast stretches and the production of TM band-ratio images. Later enhancements, chosen after the 1990 field investigations, entailed preparation of digital masks of unaltered and altered rocks and subsequent production of FCC, CRC, and selected pseudocolor density-sliced images of TM band ratios.

Small gray level differences displayed in a monochrome image can be greatly enhanced by creating a pseudocolor density-sliced image. The data are divided into several gray level ranges and then a discrete color is assigned to each range. The amount of information that can be derived from the analysis of the image data is enhanced by quantifying several easily distinguished colors.

Color-ratio-composite images displaying ratios 5/7, 5/1, and 5/4 in red, green, and blue, respectively, were produced and evaluated in the field in 1990 and 1991. As noted above, TM ratio 5/7 shows brightness contrast between rocks containing hydroxyl-bearing minerals and rocks which lack them (Fig. 3). Healthy green vegetation also gives a high response in the TM ratio 5/7 but was not confused with altered rocks in this study area because it only exists in a few isolated, easily identifiable valleys where ephemeral streams exist. TM ratios 5/1 and 5/4 were chosen to distinguish limonitic areas from nonlimonitic areas. Both ratios are high where ferric-iron absorption causes relatively low radiances in the TM1 and TM4 channels.

Limonitic areas that contain clays, sulfates, and/or other hydroxyl-bearing minerals, are expected to have high values in all three TM ratios 5/7, 5/1, and 5/4. Areas that are defined as being potentially hydrothermally altered have high values in TM ratios 5/7, 5/1, and 5/4 and appear white, pinkish white, very light blue, or yellowish white, in the CRC images.

A TM color-ratio composite image of 5/7, 5/1, and 5/4 was used in the 1990 and 1991 field investigations for an area approximately 37 km by 21 km. Although the main hydrothermally altered areas were well displayed, small compositional differences within the large area of altered rocks near the Esperanza prospect could not be distinguished by visual interpretation of this image. Therefore, a digital mask was applied to the unaltered areas prior to the production of ratio images of the predominately altered areas. To define the pixels of predominately unaltered rocks and soils, the TM ratio 5/7 was examined. A threshold DN value was selected to separate the altered areas with the highest DN values in TM ratio 5/7 and the unaltered areas which correspond with low and moderate DN values in TM ratio 5/7. The masked bands were also used to create improved ratio-composite images that enhanced subtle differences in unaltered regions.

For analysis of the potentially altered areas the most useful product was a density-sliced image of the TM ratio 5/7. This image enhanced the small gray level differences in ratio 5/7, which were difficult to interpret in the original CRC image. We chose four ranges of gray levels to apply four discrete colors. The density slice ranges were calibrated with the 1990 field data, attempting to group areas according to their relative alteration intensity. From high to low TM 5/7 values the designated colors were red, blue, yellow, and magenta. This color scheme allowed identification of the probable center of hydrothermal alteration and linear trends of the most pervasively altered rocks in the study area. The density-sliced image was then merged with the TM band 4 black-and-white image. Merging the density-sliced ratio image, which displays little topographic aspect, with the single TM band facilitated location during field investigations. The density-sliced image of TM 5/1 showed that iron-oxide and hydroxide minerals are nearly ubiquitous throughout the area having high TM 5/7 values.

Spectral measurements and field observations

Subsequent to the field evaluation during 1991, spectral reflectance of rock and soil samples collected in the field area were measured in the laboratory using the Beckman UV 5240 spectrophotometer to verify spectral responses in the TM imagery and to evaluate the usefulness of the density-sliced images and other enhancement methods used during preliminary processing. Approximately 220 spectral reflectance measurements were made of approximately 147 samples of both altered and unaltered rocks as well as several soils collected during the 1990 and 1991 field investigations. Representative samples were taken from altered zones and the various lithologies considered to be typical in the area. Figure 10 shows several reflectance spectra of altered and unaltered rocks collected within and near the large hydrothermally altered area located near the Esperanza camp (Fig. 11).

Figure 11 shows the distribution of potentially altered rocks as visually interpreted from the TM ratio images and, where feasible, corroborated by field work and laboratory spectral analysis. Interpretation of the original TM CRC images allowed us to delineate a larger, more precise distribution of hydrothermally altered rocks in the Esperanza district than is shown on the unpublished geologic map (1984, J. Munoz). Several additional areas were delineated that had not previously been mapped. The Atacama gravel deposits were difficult to distinguish from the altered rocks, because the unit consists partially of sedimentary accumulations of altered rocks. Also, additional areas were mapped as altered on the outskirts of the principal altered area, but the spectral analysis results did not reveal common alteration minerals. Thus, an attempt to refine the mapping was undertaken during the second field visit.

The density-sliced images with the unaltered areas masked were interpreted in the field, and samples were collected from areas within the four density levels of the TM ratio 5/7, as well as outside the potentially altered areas. Evaluation of the spectral measurements of these field samples aided in the revision of the alteration map.

Discussion

Analysis of the density-sliced images permitted elimination of false hydrothermal alteration anomalies and refinement of the main area of alteration. Rocks containing alunite dominated the samples taken from within the areas that correspond with the highest density-slice level. More than 70 percent of the samples of this group showed evidence of argillic alteration, such as kaolinite and mixed-layered clays. Limonite was fairly consistent throughout the four density levels and only decreased outside the area mapped as potentially altered. Jarosite was twice as common in the highest level compared to samples collected from areas within the next two lower density levels and was absent in the lowest level.

In the second level there was a slight increase in the number of samples containing limonite, a decrease in jarosite occurrences, but approximately 40 percent contained argillic minerals. Although

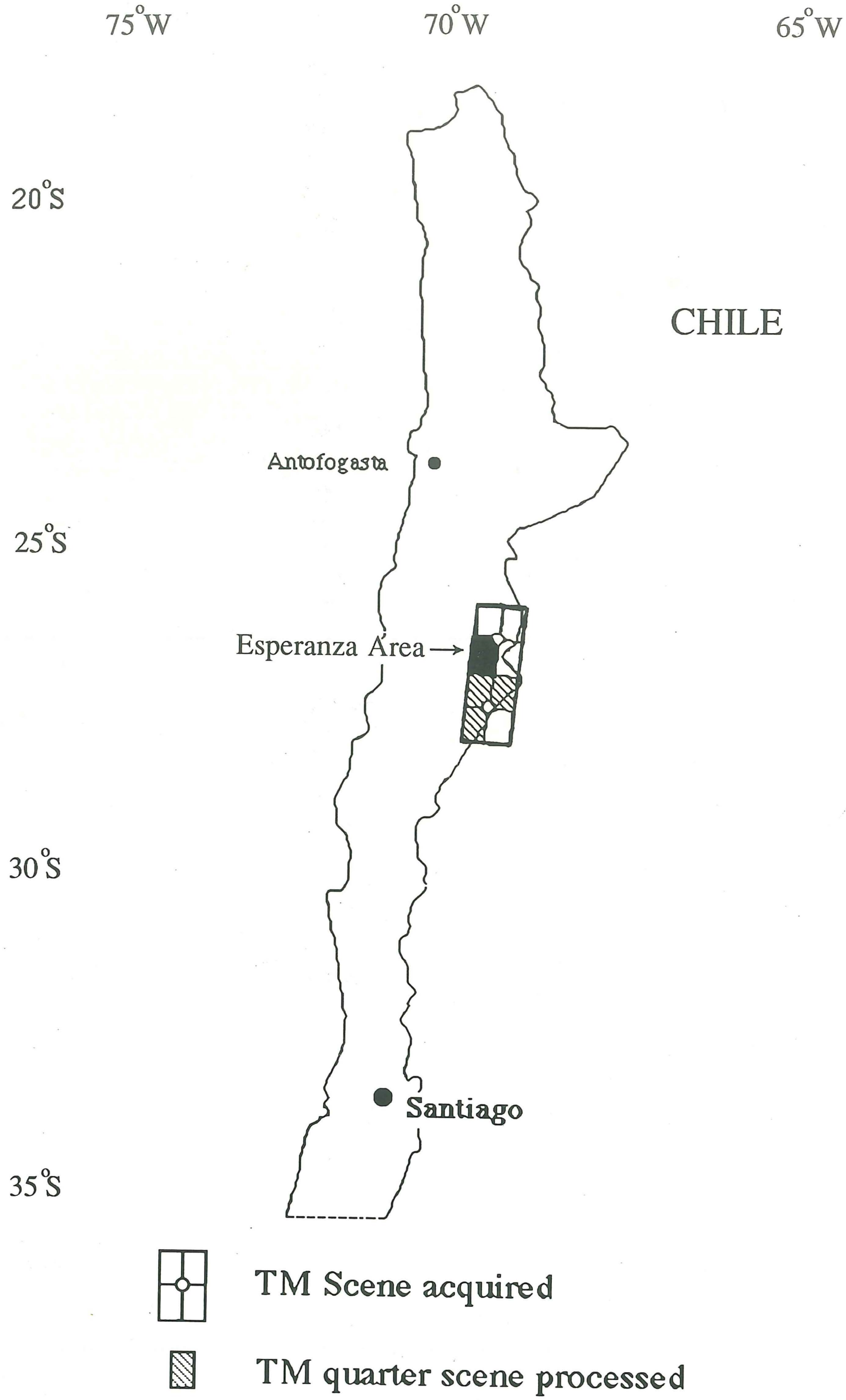

Figure 9.— Map showing locations of the Esperanza, Chile study area (black) and Landsat TM image quadrants that were processed (black and ruled areas).

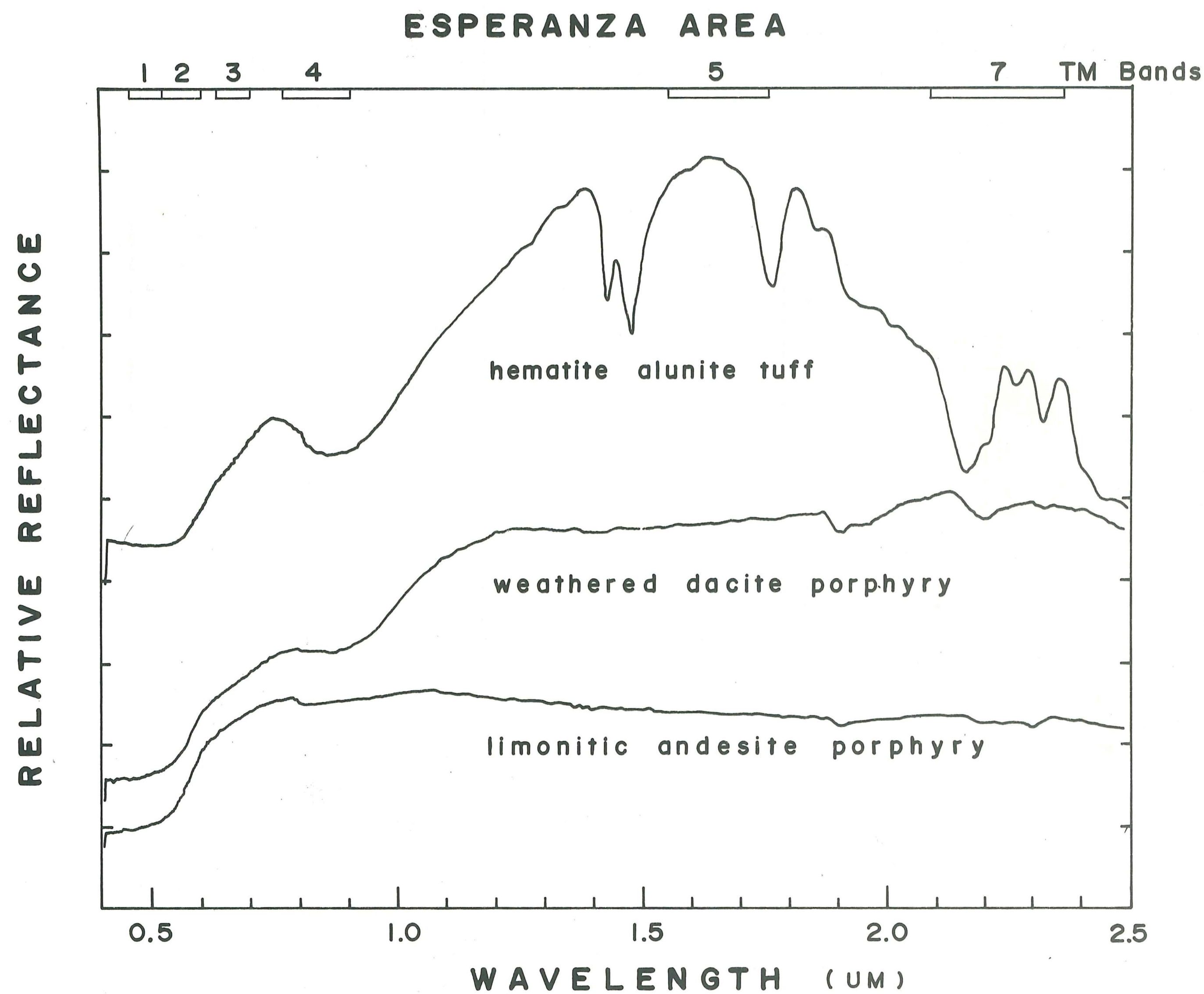

Figure 10.— Visible and near-infrared reflectance spectra of hydrothermally altered tuff and dacite porphyry and unaltered andesite porphyry samples from the Esperanza study area. Landsat TM bandpasses shown at top.

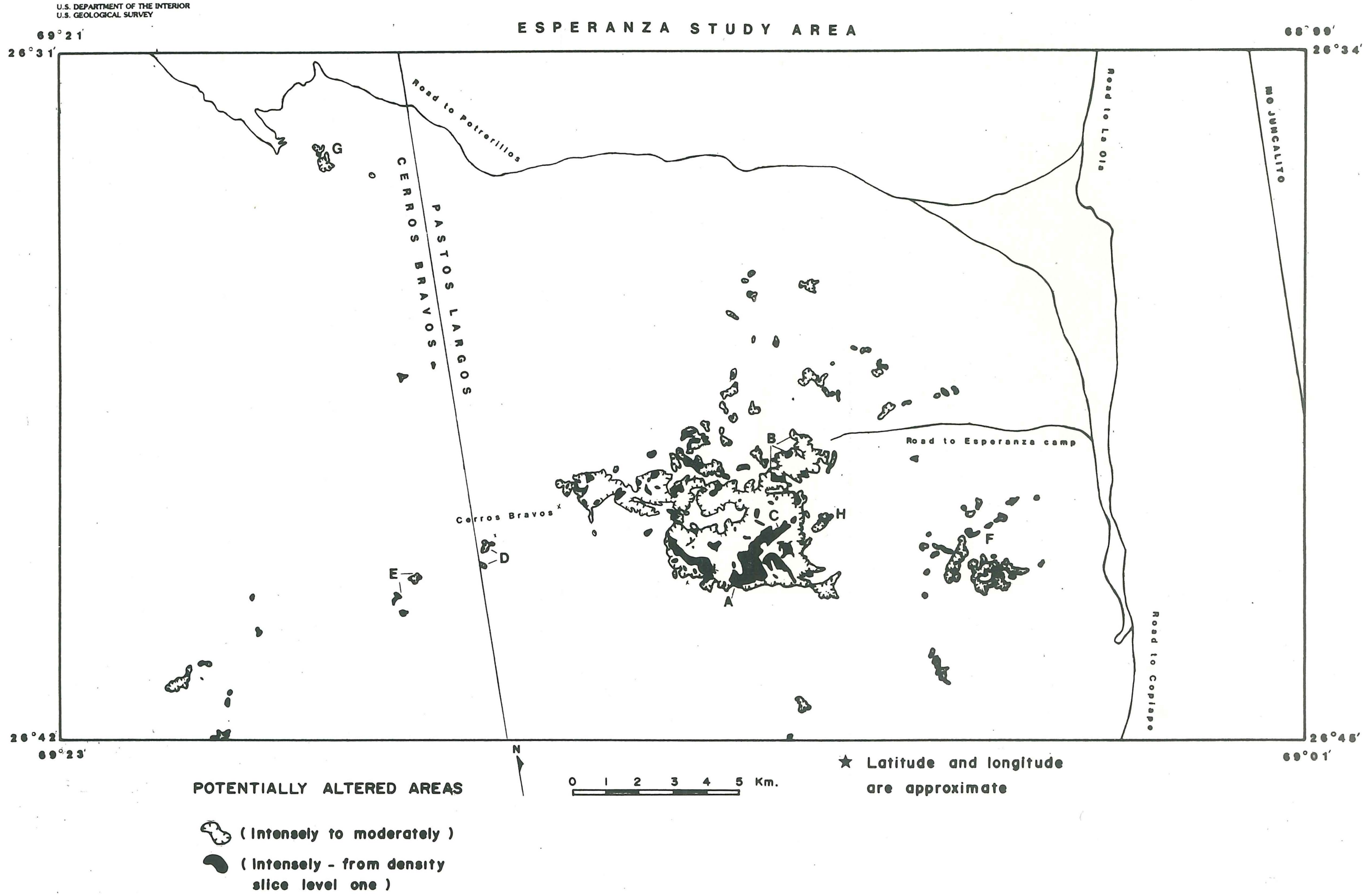

Figure 11.— Map showing the distribution of intensely hydrothermally altered rocks and intensely to moderately hydrothermally altered rocks within the area covered by the TM image quadrant of the Esperanza study area. Areas A Through H are discussed in the text.

the number of samples in the lowest level that contain iron-oxide and hydroxide minerals is similar to that of the other levels, the lowest level showed little additional evidence of alteration minerals in the spectral analysis of the rocks.

The third level of the density-sliced image of TM ratio 5/7 consists of areas of moderately altered rocks. The number of samples containing alunite decreased by approximately 60 percent compared to the number of alunite samples in the highest level, and jarosite and clay minerals were less prevalent. The last level of the density-sliced image consists mainly of unaltered rocks and, therefore, was eliminated from the final map (Fig. 11).

Although known false anomalies were eliminated from the final map, some unevaluated areas may not be hydrothermally altered. In particular, the Atacama gravel deposits in the area introduced ambiguities because they are commonly made up of altered materials, but the majority of this unit occurs in the lowest level of the density sliced image and, as stated above, these areas were eliminated. In addition, ignimbrite exposed south of the junction of the roads to La Ola and Potrerillos were erroneously mapped as altered in the initial CRC image interpretation, but this was corrected using the density-sliced image.

The original CRC image, which consisted of TM 5/7, 5/1, and 5/4, was adequate to distinguish altered from unaltered rocks, but by segregating altered from unaltered rocks and producing a density- sliced image of the TM ratio 5/7 we refined the hydrothermal alteration map by reducing the number of false anomalies and increasing the detail within the altered areas. The largest area in the highest level of the density-sliced image marked A in figure 11 probably represents the center of hydrothermal activity where the most pervasive alteration would be expected. A prominent northeast-trending zone consisting of three anomalies from the highest level in the density-sliced image was identified at the map location marked B and corresponds to a mineralized ridge of silicified pyroclastic rocks known as Santa Rosa. Another linear trend is present at the area marked C and corresponds to a northeast-oriented ridge that consists of highly argillized and silicified dacitic rocks. Previously unmapped altered areas include D and E near Cerros Bravos to the west of the main altered area, and the group of anomalies marked F to the southeast of Cerro Carachapampa. At location G, the alteration associated with the abandoned Tinaja prospect was also identified.

One area, which trends northeast, marked H in figure 11, is enigmatic. Although the volcanic rock float shows no evidence of hydrothermal alteration in the field, the area is in the second highest level of the density-sliced image. A possible explanation for this false anomaly, which is dominated by fresh andesites, is the deposition of gypsum from near surface ground water or meteoric water. The waters could be transporting calcium sulphate in solution and gypsum may crystallize in seams and veins as secondary deposits. In the field, gypsum is present as fracture and pore fillings in the soil, as well as crystals on the surface.

Summary, Esperanza study area

Field evaluation of the initial TM 5/7, 5/1, 5/4 CRC image showed that the distribution of hydrothermally altered rocks was reasonably well displayed. However, analysis of 4-level density-sliced TM 5/7 image permitted refinement of the initial map of hydrothermally altered rocks by aiding in identification of unaltered areas, such as much of the Atacama gravel deposits, and delineation of the most intensely altered areas. The effectiveness of this method for mapping hydrothermally altered rocks in this area stems from the paucity of vegetation. In more verdant areas, its effectiveness would be limited by the DN overlap of hydrothermally altered rocks and vegetation.

PERU STUDY AREAS

For the study areas in southern Perú CRC images incorporating TM ratio combinations of 5/7, 3/1, and 4/3 or 5/7, 5/1, and 4/3 displayed as red, green and blue, respectively, were produced for 4 image quadrants at 1:200,000-scale (Fig. 12). The rationale for selecting these ratios is discussed in previous sections of this report. Four 1:50,000-scale CRC images were produced for detailed studies within these image quadrants. Digital masks were used in some areas for snow, water, and vegetation to enhance the display of potentially hydrothermally altered rocks. In addition, black-and-white single-band images and

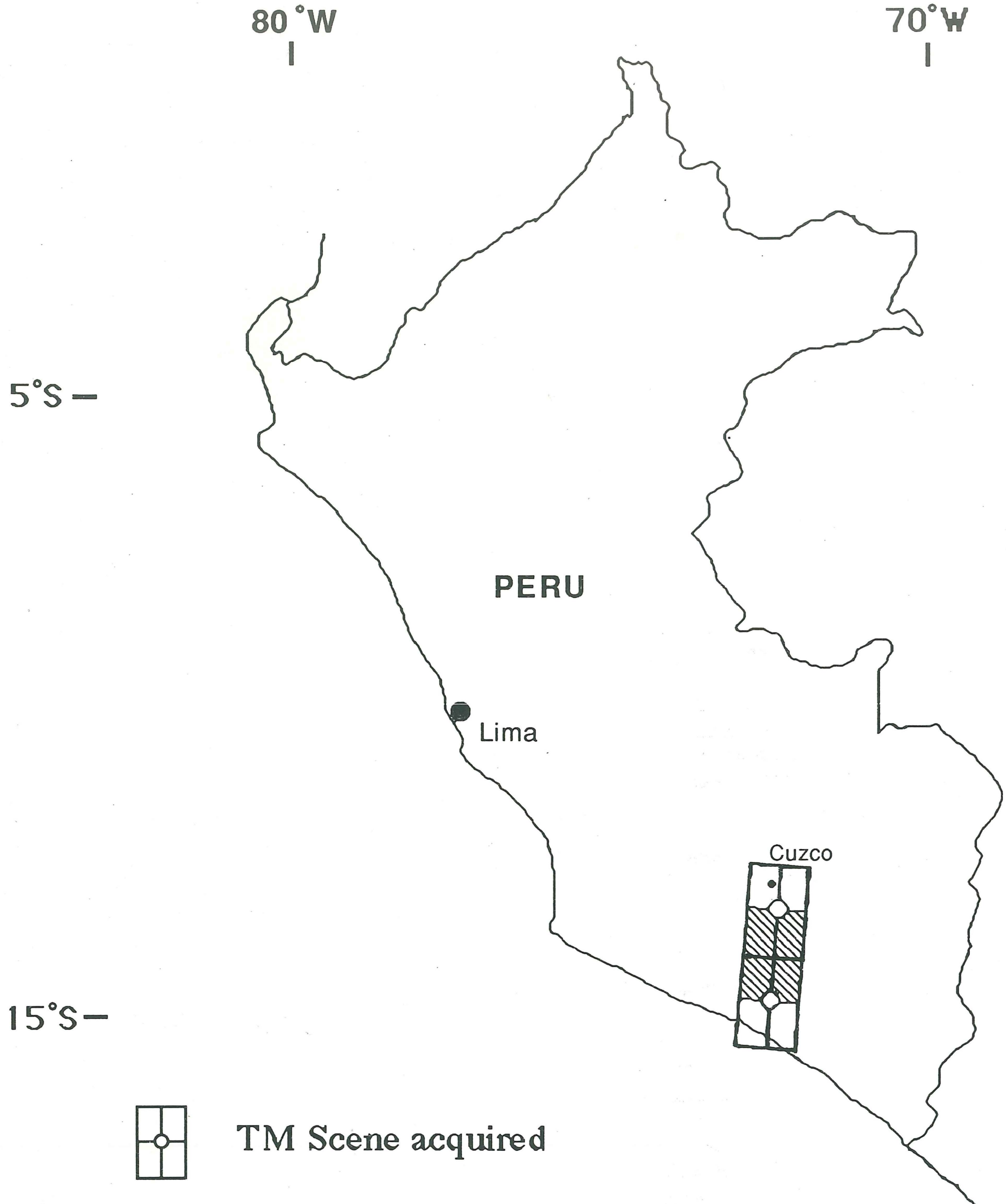

Figure 12.— *Map showing the locations of Lndsat TM image quadrants that were processed (ruled area) within Perú.*

FCC images using TM band 7,4, and 1 or 5, 4, and 1 were produced for each quadrant.

For the Orcopampa area potentially hydrothermally altered rocks were identified from interpretation of a color-ratio-composite image. The locations of these areas were compared with an unpublished map showing the distribution of argillically altered rocks at the Orcopampa mine. This comparison revealed a very high correlation between the known alteration and the areas interpreted from the Thematic Mapper CRC image, suggesting that the other areas in the image that have similar spectral responses may represent hydrothermally altered rocks. An area northwest of the immediate vicinity of the Orcopampa mine, the Umachulco sector, was identified in the CRC as potentially altered and later described in the field by INGEMMET geologists as an extensive area of hydrothermally altered rocks within an eroded volcano, thus supporting the use of the CRC images to identify new areas of hydrothermally altered rocks. Other such identified areas in this relatively unexplored and remote region warrant more intensive field investigations.

CONCLUSIONS

The results of this study demonstrate the usefulness of Landsat TM image analysis for mapping volcanic and structural features and lithologic units in the Altiplano region, especially hydrothermally altered rocks. The effective map scales are 1:50,000 and smaller scales. Black-and-white images of individual TM bands and CIR images display volcanic and structural features best, whereas CRC images are most useful for delineating lithologic units. CRC images were used to map hydrothermally altered rocks, whereas the CIR images aided delineation of the unaltered rocks. Image quality and interpretability was improved by making a correction for atmospheric scattering and employing digital masks for snow and water. Density-sliced TM 5/7 ratio images provided an objective method for mapping different levels of alteration intensity and displaying patterns related to volcanic activity and structural control. Because of the paucity of vegetation, incorporation of a TM 4/3 ratio to distinguish vegetation in the CRC images was not necessary for most of the region. This permits usage of other ratios to aid in discrimination of lithologic units. The optimum ratio and color display combination in low vegetation-cover areas is TM ratios 5/7, 5/1, and 5/4 in red, green and blue, respectively. In areas where vegetation causes image display and interpretation limitations a digital vegetation mask was very useful. The optimum CRC image in these areas is the same combination used in less vegetated areas, providing a digital vegetation mask is applied prior to ratioing. In some areas with intermediate amount of scattered vegetation good results were obtained by replacing the TM 5/4 ratio with TM 4/3, instead of using a vegetation mask.

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