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INTERPRETATION OF LANDSAT THEMATIC MAPPER SATELLITE IMAGERY AT LOS AZUFRES GEOTHERMAL FIELD, MICHOACAN, MEXICO

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ABSTRACT

This report documents part of a cooperative study by CFE and UURI of a Landsat 5 image of the Los Azufres geothermal area and its surroundings. The objective was to determine if processing and interpretation of satellite imagery are useful in volcanic environments for mapping structures, hydrothermal alteration, rock types and/or soil geochemical anomalies manifest in vegetation. Several processing steps were carried out using the ERDAS image-processing system installed on an AT-equivalent PC at UURI in an attempt to detect characteristic signatures from hydrothermally altered areas and to enhance linear and other structurally related geologic features.

A great deal of structural information is recorded in the Landsat image. Most of the interpreted linear features are believed to be due to faulting and fracturing, and there are more interpreted linears than there are mapped faults. The additional information contributed from the image interpretation may prove useful in planning for further development of the Los Azufres area.

Signatures reasonably characteristic of hydrothermally altered areas were developed after considerable experimentation with various false-color images of the direct digital data and of derived band ratios. This is a significant result because it implies that the method may be useful in helping to assess other areas of known geothermal occurrence which are less thoroughly mapped than is Los Azufres.

We believe that satellite imagery interpretation may contribute cost effectively to an exploration program by (1) outlining areas of strong and/or young faulting, (2) outlining areas where faulting and fracturing are more intense, (3) detecting hydrothermal alteration with a reasonable degree of reliability after calibration over known alteration, (4) outlining areas of young volcanic deposits, and (5) helping to guide geologic field work and prioritize areas. The cost per unit area of coverage is relatively small compared to some other techniques such as geologic mapping.

INTRODUCTION

Although remote sensing and satellite imagery interpretation are being developed for petroleum and minerals exploration and for other geological applications, there has been little research and technology development specifically for geothermal exploration. This report documents the status of part of a cooperative study by CFE and UURI of a Landsat 5 image of the Los Azufres geothermal area and its surroundings. Landsats 4 and 5 carry an instrument package known as the Thematic Mapper (TM) which senses reflected energy in 6 bands in the visible and infrared (IR) portion of the spectrum and radiated energy in 1 band in the thermal infrared.

The objective of this study was to determine if processing and interpretation of satellite imagery are useful in volcanic environments for mapping structures, hydrothermal alteration, rock types and/or soil geochemical anomalies manifest in vegetation. The synoptic view afforded by satellite imagery makes it ideal for seeing geomorphic features related to structure and rock type. In addition, some of the sensor bands on the TM instrumentation package were chosen to help maximize chemical information on rocks and soils. Thus, the TM data have the potential for detecting and mapping geologic information needed for geothermal exploration and development.

DIGITAL PROCESSING SYSTEM

A full Landsat 5 TM image, approximately 34,000 sq km centered roughly on the Los Azufres geothermal area, was acquired from EOSAT by UURI in digital form. The pixel size is 30 m by 30 m for the visible and reflected IR bands (Bands 1 - 5 and 7) and 120 m by 120 m for the thermal IR band (Band 6). An area of about 900 sq km centered on the

Los Azufres field was selected for study, and a subset of the digital data for this area was placed in a working disk file on an IBM AT-compatible personal computer (PC). The processing software installed on the PC is the ERDAS system, a powerful digital-processing package available from ERDAS, Inc. The PC is linked to a 767-pixel by 512-pixel color video monitor and a Tektronix 4696 ink-jet color printer. This system allows interactive image processing, with the results of selected images sent to the printer for hard copy. Photographs of reasonably high quality can also be made directly from the color monitor screen.

IMAGE PROCESSING AND INTERPRETATION

Several processing steps were carried out in an attempt to detect a characteristic signature from hydrothermally altered areas and to enhance linear and other structurally related geologic features. One of the steps was to experiment with different false-color images produced by displaying various combinations of TM bands on the three primary-color channels (red, green and blue) of the color monitor. Since the TM image contains 7 bands of digital information, it can be shown that by using all available band combinations, including the same TM band on more than one monitor channel, 343 different false-color images can be produced. Not all of these images would be totally unique in information content, although they would each appear as distinct combinations of colors.

Figure 1 shows a color photographic print taken from the screen of the color monitor with a 35 mm SLR camera using Ektachrome 200 slide film. This image was judged as excellent for structural information, and it also displays a reasonably definitive signature in hydrothermally altered areas. The image was made by displaying TM band 7 on the red channel of the color video monitor, TM band 4 on the green channel and TM band 2 on the blue channel, hereafter noted as a (7, 4, 2) image. A contrast-stretching process was applied by using an algorithm in the ERDAS system. Contrast stretching expands the measured range of digital numbers characterizing each band of the image to a larger range in order to improve the contrast among colors and to increase the amount of information displayed.

Figure 1 covers about 110 sq km centered on the Los Azufres field. The short edges of the image strike about N 08 E. Because rectification was not performed on the image, the north-south and east-west scales of the photo are not equal, and care must be used in comparing the photo to maps of the area. The north-south dimension of the image is compressed about 16 per cent compared to the east-west dimension. Three prominent lakes can be seen in dark blue to black colors; Bordo Laguna Verde in the north-central portion of the photo, Laguna Larga in the west-central portion and Laguna Llano Grande in the east-central portion. These lakes serve as features easy to identify on both the photo and on maps of the area. The volcano San Andres appears on the east edge of the view just north of the center line. Pinkish areas on the west, northwest and northeast are fallow fields in the lower elevations surrounding the Los Azufres volcanic upland.

In order to understand the colors shown on Figure 1, we must present some background information. The visible part of the electromagnetic spectrum extends from about 0.4 to 0.7 micrometers. TM Band 1 is in the visible blue, TM Band 2 is in the visible green and TM Band 3 is in the visible red. The remaining bands are beyond the visible spectrum, in the infrared. Figure 2 shows the TM bands along with typical reflectance spectra for unaltered rock, hydrothermally altered rock and vegetation (Sabins, 1987, p. 85). Also shown for comparison are the Landsat Multispectral Scanner (MSS) bands, an older generation of instrumentation. The vertical axis indicates the percentage of incident light that is typically reflected from outcropping rock or soil surfaces and from vegetation. Of course, orbiting satellites measure only the light that is reflected or radiated from the earth's surface. Low reflectance means that there is high absorption of the sun's incident energy. Higher responses in all TM bands simultaneously give light colors, especially whites and near whites, on false-color images. Lower responses, indicating absorption, give darker colors.

Figure 2 shows that rocks and soils have broad, fairly smooth reflectance spectra that peak roughly around TM Band 5. This is true both for altered and unaltered rock. Vegetation has reflectance peaks in TM Bands 2, 4, 5 and 7 and strong absorption in TM Bands 1 and 3.

Figure 1 is a (7, 4, 2) image. Since the reflectance of vegetation is strongest for TM Band 4 and this band is mapped onto the green channel of the color video monitor, we would expect vegetation to appear green on the image, and it does. The slopes of the Los Azufres volcanic feature are covered with dense conifer trees and brush. Water reflects visible light to a limited extent, but absorbs the infrared. Thus, water usually appears as dark colors on false-color images. On Figure 1, it is dark blue to black. The less heavily vegetated to unvegetated areas of the image have high reflectance in all of the bands used, and appear in light colors. These light colors are slightly dominated by TM Band 2 in areas that are believed to be fallow fields, and thus appear in shades of red on the image. In areas of hydrothermal alteration, high reflectance is observed in all

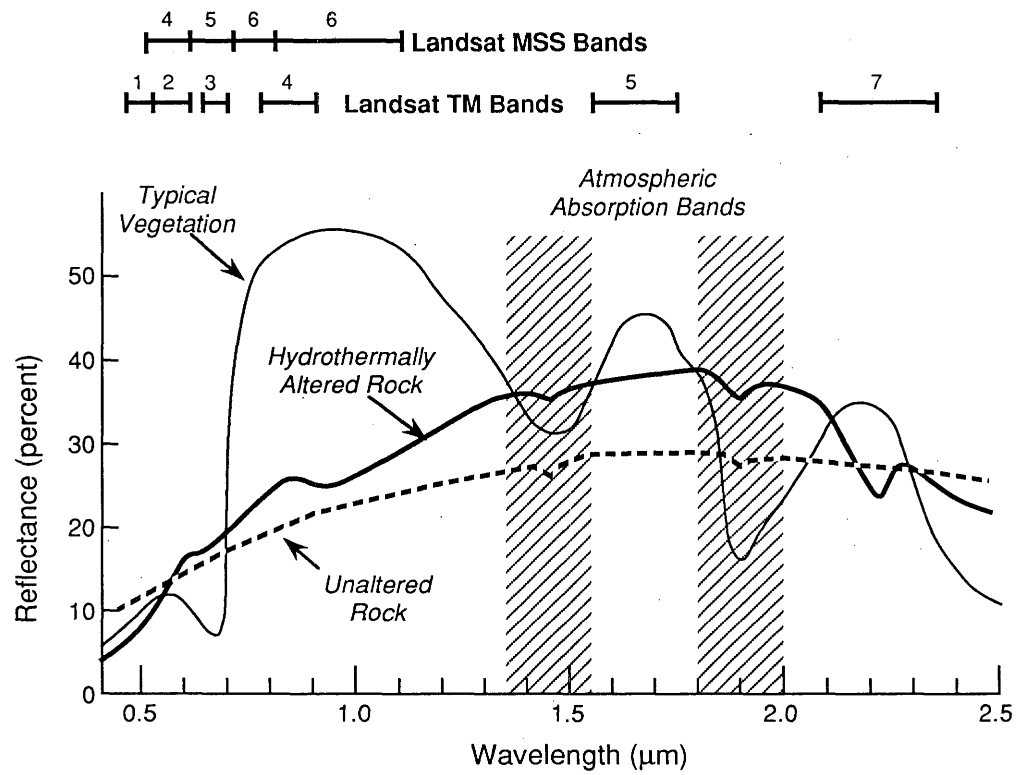

Figure 2. Spectral bands for TM and MSS systems. Reflectance curves for vegetation, unaltered rocks, and hydrothermal altered rocks. From Sabins (1987, Fig. 4.14).

bands. TM Band 7 seems to predominate slightly, producing a bright bluish-white color over altered areas, as discussed below.

Structural Interpretation

The structural complexity of this area is clearly shown in Figure 1. The Los Azufres volcanic complex, encompassing virtually the entire photo, is shown to be subcircular in plan, extending westward from the young, high vent of San Andres. Prominent linears trend east-west, the main structural direction in the Mexican Neovolcanic Belt. Less prominent trends are north to northwest and northeast-southwest. Figure 3, an overlay to Figure 1, gives a reasonably detailed plan of the linear features on the (7,4,2) image. It is quite clear that many of the lineations represent faulting and/or fracturing and that the Los Azufres geothermal system occurs in a highly fractured area.

Comparison of Figures 1 and 3 with Figure 4, a geologic map simplified from Razo et al. (1989) and distorted to approximately overlay the image, shows that essentially all of the mapped faults are indicated on the false-color image. In fact, there are more linears interpreted from the image than there are mapped faults. This is not a surprising result in view of the problems in geologic mapping at Los Azufres posed by the heavy vegetation and cover of residual soil and organic material.

Having the most complete information possible on the faulting and fracturing is important for planning further drilling of exploration, production and injection wells since fluid movement in the reservoir is believed to be controlled predominantly by fractures. Our conclusion is that further, more detailed study of this and other processed images from the TM data may be able to supplement the geologic mapping of fluid-controlling structures and/or indicate areas where further field geologic work should be undertaken.

Another useful image from the structural standpoint was produced by calculating numerical band ratios, namely the color-ratio composite (6/5, 6/4, 6/7). Band 6 is the thermal infrared band, and has a spatial resolution of 120 m. An image of this band alone appears fuzzy compared to images from other bands, which have 30-m resolution. However, by forming ratios of Band 6 with the higher-resolution bands, detail is preserved along with the thermal IR information.

The thermal IR band responds to variations in surface temperature, and it might seem that this band should reflect the surface geothermal phenomena. However, the surface temperature is influenced to a much higher degree by the amount of solar radiation and the presence or absence of vegetation than it is by heat flux from the subsurface. Thus, the known geothermal manifestations do not stand out on this image. However, a great deal of structural detail is shown in the (6/5, 6/4, 6/7) image. Most of the structural detail results from shadowing due to topographic variation, which reflects underlying geologic structure.

The locations of several of the TM measurement bands on the electromagnetic spectrum were chosen to provide chemical information on soil or rock outcrop of interest to exploration geologists. The minimum in the reflectance of hydrothermally altered rock in the middle of TM Band 7 is due to absorption of incident energy by the OH- radical in minerals. Chief among the hydrated minerals are the clays and zeolites, which are typically produced during hydrothermal alteration of volcanic rocks. The reflectance of altered rocks reaches a maximum in TM Band 5. Alteration and weathering can also produce iron oxide minerals which have weak reflectance in TM Band 1 (visible blue), moderate reflectance in TM Band 2 (visible green) and strong reflectance in TM Band 3 (red).

In spite of these useful generalizations, image interpretation to a large extent is carried out empirically by creating various false-color images and observing correlations with geology that can be used to extend the information on the geologic map. In this study, numerous false-color images were examined by displaying various combinations of bands on the three color channels of the monitor. The purpose of this work was to determine which of the images, if any, would yield a reasonably characteristic signature in the areas of known hydrothermal alteration and which would show the structure best. Several of the false-color images showed hydrothermal alteration well where there is no tree cover. Perhaps the most promising band combination was (7, 5, 2). Areas known to be hydrothermally altered appear in a bright blue-white color that is quite characteristic.

Figure 1, the (7, 4, 2) image, also shows this bright blue-white color over altered areas, although not quite as well as the (7, 5, 2) image. Interpreted areas of hydrothermal alteration, based on examining the photo, are shown on Figure 3. The criteria for making this interpretation were that the image show high intensity (brightest spots on the image), bluish-white color. Reddish-white, even bright reddish-white, does not correlate well with known alteration. Intercomparison of Figures 1, 3 and 4 shows a reasonably good correlation between the interpreted and actual occurrences of alteration.

Standard image processing seems unable to detect alteration beneath vegetation. The Los Azufres geothermal area is covered by dense conifers, and rock and soil are covered in many places by a thick layer of organic debris consisting mostly of conifer needles. The characteristic blue-white color appears only in areas where vegetation is missing due to natural causes or man-made clearing such as drill sites. This poses a limitation to application of imagery interpretation for alteration mapping at Los Azufres while at the same time indicating that similar application in less vegetated areas may be possible.

Several color-ratio images were also created in an attempt to identify altered soils (Drury, 1987). Ratio images enhance subtle brightness differences and help subdue the effects of topography and shadows. Abrams (1984) found that the image (5/7, 3/2, 4/5) produced characteristic yellow colors over altered areas at the Rosemont and Silverbell porphyry-copper deposits in Arizona. In his study, the color-ratio composite (5/7, 5/4, 3/1) produced satisfactory results with OH- bearing soils appearing as yellows, HOH (moist vegetation canopy) as magenta, and Fe3+ as cyan. The image (5/7, 3/4, 5/1) was also found to produce a reasonably characteristic color over areas of known hydrothermal clays. However, in our work we found that the color-ratio composite (3/4, 7/4, 5/4) produced the most highly characteristic color correlation with known areas of alteration. The (3/4, 7/4, 5/4) image is shown on the color plate as Figure 5. Because TM Band 4 is dominated by the effects of vegetation in the Los Azufres area, this color-ratio composite shows the vegetated areas as very dark colors, mostly blues. The three prominent lakes show as bright red. Soils in fallow fields in the lower areas surrounding the Los Azufres highlands are indicated in light bluish-white shades, as are unaltered soils in several small basin areas within the Los Azufres upland. Areas of known hydrothermal alteration are shown in a very light pink shade. Detailed comparisons of the pink areas with the mapped position of alteration indicate a very good correlation.

Rock Type and Vegetation

None of the images examined appear capable of distinguishing with certainty any of the various rock types that occur in the Los Azufres area. Some of the green color variations shown on Figure 1 are caused by changes in vegetation, but the control on these vegetation changes appears to be related predominately to altitude.

CONCLUSIONS

This study shows that useful new information can be generated from the interpretation of Thematic Mapper satellite data. A great deal of structural information is recorded in the Landsat image. Most of the interpreted linear features are believed to be due to faulting and fracturing, and there are more interpreted linears than there are mapped faults. The additional information contributed from the image interpretation may prove useful in planning for further development of the Los Azufres area.

Signatures reasonably characteristic of hydrothermally altered areas were developed after experimentation with various false-color images of the direct digital data and of derived band ratios. This is a significant result because it implies that the method may be useful in helping to assess other areas of known geothermal occurrence which are less thoroughly mapped than is Los Azufres.

It is apparent that the kind of information derived from the present study would be best applied in geothermal development at an early stage in exploration. The type of structural interpretation shown on Figure 3 would be valuable to the field geologist at the outset of detailed mapping. It could point out the probable locations of the youngest and strongest faults in an area as well as the general degree of faulting and fracturing compared to regional faulting and fracturing. More efficient field work would result. Such structural information may also prove useful in ranking geothermal prospects for further work even before detailed geologic mapping is attempted. Once signatures characteristic of hydrothermal alteration are established for a region, the processed image would quickly point out specific areas high in priority for field checking.

Of course, satellite imagery interpretation benefits from correlation with other earth science information and should not be used alone in geothermal exploration. It is merely one potential component in an exploration program. We believe that satellite imagery interpretation may contribute cost effectively to an exploration program by (1) outlining areas of strong and/or young faulting, (2) outlining areas where faulting and fracturing are more intense, (3) detecting hydrothermal alteration with a reasonable degree of reliability after calibration over known alteration, (4) outlining areas of young volcanic deposits, and (5) helping to guide geologic field work and prioritize areas. The cost per unit area of coverage is relatively small compared to some other techniques such as geologic mapping.

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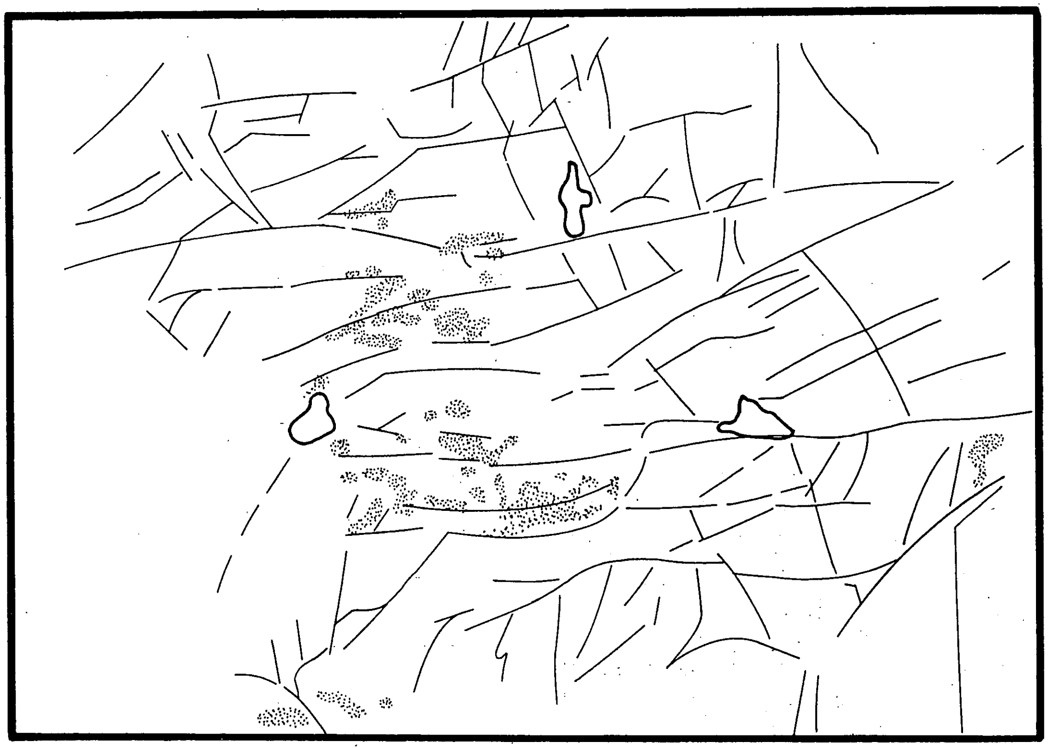

Figure 3. Selected linear features and interpreted hydrothermal alteration from Landsat TM (7, 4, 2) image.

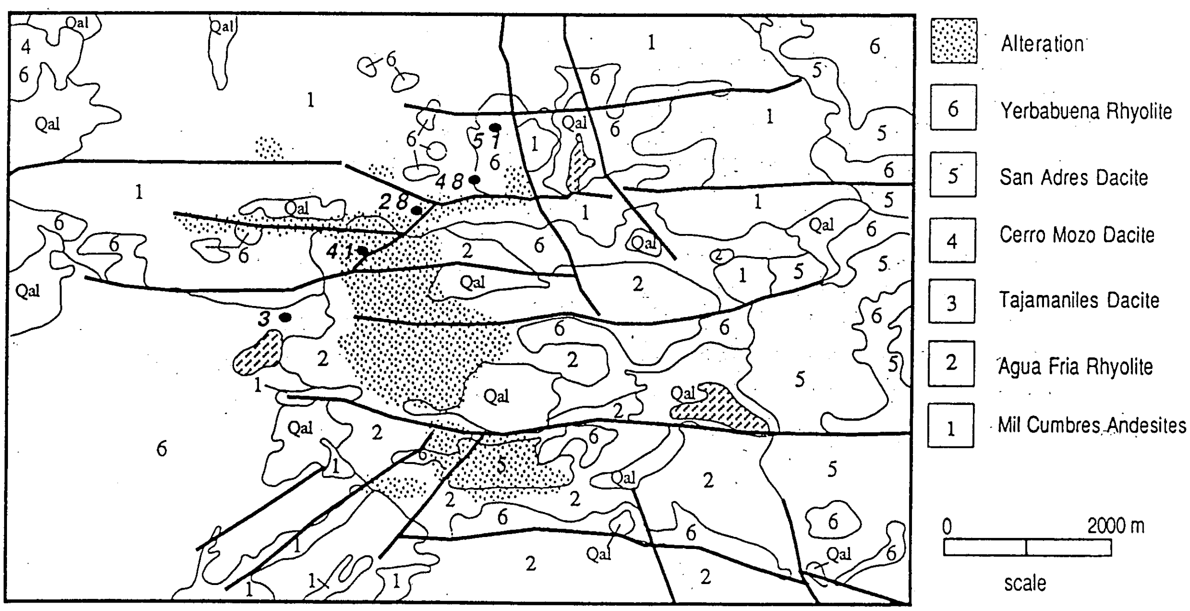

Figure 4. Geologic map of Los Azufres area after Razo et al. (1989). Distorted to approximately overlay Figures 1 and 5.

Figure 1. False color image (7, 4, 2) of the Los Azufres geothermal field and surroundings.

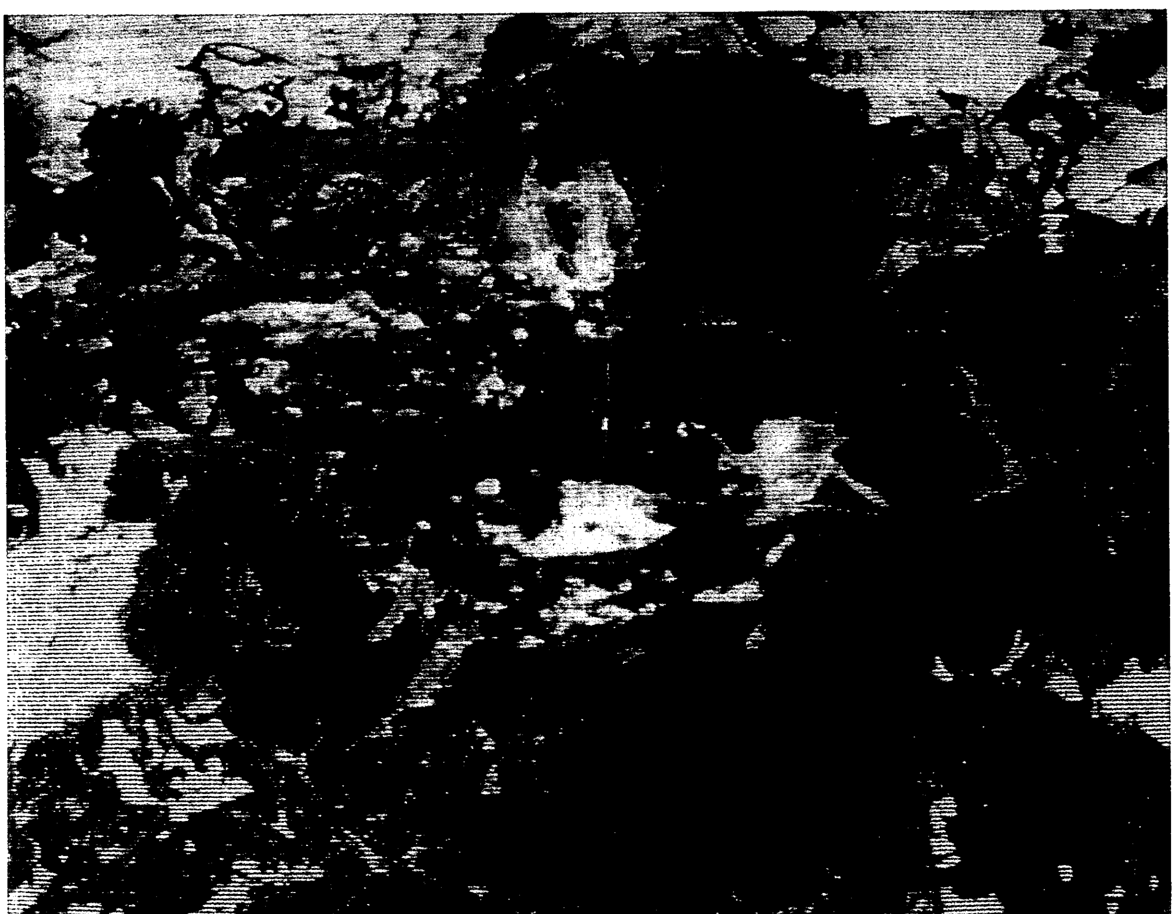

Figure 5. False color band ratio image (3/4, 7/4, 5/4) of the Los Azufres geothermal field and surroundings.