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CHARACTERIZATION OF MINE WASTE MATERIALS AND HYDROTHERMALLY ALTERED ROCKS IN THE RIO TINTO MINING DISTRICT (SOUTHWEST SPAIN) USING HYMAP DATA

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RESUMEN: Se han registrado datos aeroportados de alta resolución espectral en el área de las minas de Río Tinto, uno de los yacimientos de sulfuros metálicos más importantes del mundo. Las operaciones mineras, que datan de épocas pre-romanas, han generado un gran volumen de escombreras y residuos mineros. La meteorización de estos materiales y de las rocas mineralizadas aflorantes han originado una intensa contaminación de metales pesados en los sedimentos aluviales del ríoTinto. Los datos registrados por HyMap, una vez corregidos del efecto atmosférico y calibrados utilizando medidas in situ de reflectividad, han permitido identificar pirita, jarosita, yeso, copiapita, coquimbita y otros minerales de Fe^{3+} en escombreras y materiales resultantes del tratamiento mineral, y yeso, copiapita, melanterita, rozenita y minerales de Fe en los aluviales del río Tinto. Otros minerales, producto de la alteración hidrotermal de las rocas volcánicas, como clorita hidrotermal en Cerro Colorado y alteración sericítica en áreas externas a las mineralizaciones de sulfuros han sido también identificados por este método.

ABSTRACT: High spectral-resolution airborne HyMap reflectance data were acquired over the Río Tinto mines, one of the largest base-metal sulfide deposits in the world. Mining activities, dating from pre-Roman times, have produced huge quantities of pyritic tailings and dump materials. Weathering of mine waste and natural mineralized rock has caused acid mine drainage and intensive heavy-metal pollution of the RioTinto alluvium. Analysis of HyMap data, after calibration using in situ spectral reflectance measurements, resulted in identification of deposits containing a large variety of minerals, including pyrite, jarosite, gypsum, copiapite, coquimbite, and several ferric-iron minerals in mine dumps and tailings in the mine area. In alluvium along the Rio Tinto, gypsum, copiapite, melanterite, and rozenite, as well as ferric-iron minerals were mapped. Hydrothermal alteration mineral assemblages in waste materials and in the volcanic country rocks were also identified, including hydrothermal chlorite in the Cerro Colorado open pit mine and sericitic alteration in outer areas around sulfide mineralized deposits.

Key Words: Hyperspectral airborne data, acid drainage, heavy metal pollution, hydrothermal alteration, Río Tinto.

INTRODUCTION

High spectral-resolution airborne reflectance data (0.4 to 2.5 micrometers) were recorded of the Rio Tinto and Aznalcóllar mine areas by using the HyMap imaging system (Fig. 1). The flights were conducted by the Instituto Geológico y Minero de España (IGME) in response to environmental concerns about mine-waste, which was heightened by the April 1998 tailings pond spill at the Aznalcóllar Mine. Fine-grained sulfides and acid water flooded the Guadiamar River Valley more than 40 km downstream. Several Daedalus Airborne Thematic Mapper (ATM) flights were carried out by the Instituto Nacional de Técnica Aeroespacial (INTA) during and after the sludge removal. These data proved to be very useful for mapping the remnant sludge-polluted soils because of the low overall reflectance of the pyritic sludge (Lopez Pamo *et al.*, 1999; Antón-Pacheco *et al.*, 2000). However, minerals in the pyritic slurry and its alteration products could not be identified due to the low spectral resolution of the ATM system.

Many mine-waste minerals exhibit spectral absorption features in the 0.4–2.5 micrometer wavelength region (Hunt and Ashley, 1979), and analysis of high spectral-resolution reflectance images permits identification of these minerals. This type of airborne imagery has been used extensively in mineral exploration to map minerals in hydrothermally altered rocks. During the last decade, these images have been used for identifying iron minerals, clay minerals, and sulfate minerals in sulfide mine environments. These minerals may have high heavy-metal content and can be used as pathfinders of potential sources of surface-acid drainage (Munts *et al.,* 1993; King *et al.,* 1995; Swayze *et al.,* 2000). Also, in mine sites, high spectral resolution images can be utilized to map mineral distributions more comprehensively and economically than can be achieved by conventional methods alone.

THE RIO TINTO MINING DISTRICT

This report briefly describes the results of the initial analysis of the HyMap data of the Río Tinto mine area. The Río Tinto mining district, located in the Huelva province, is known worldwide for its enormous polymetallic sulfide deposits. This area forms part of the Iberian Pyrite Belt (IPB) (Fig. 1), which comprises about 90 polymetallic sulfide deposits hosted in an upper Devonian-early Carboniferous volcanic-sedimentary sequence. Mining has been active since pre-Roman times, generally without consideration for the environmental impact. During the last two centuries alone, operations in about sixty mines have resulted in extraction of 280 Mt of pyrite ore (Strauss *et al.,* 1974) of which about the half were from the Río Tinto deposits.

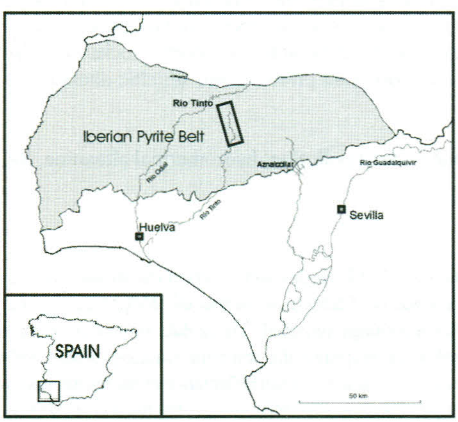

Figure 1. Location of the study area

The main Río Tinto sulfide deposits are the San Dionisio (Corta Atalaya y Alfredo), Cerro Colorado and Planes–San Antonio, which total more than 500 Mt. They are located at the top of a series of rhyolitic and dacitic volcanic rocks within the tuffites and shales of the so–called upper "transitional series" (Garcia Palomero, 1980). The massive sulfide mineralized deposits occur as stratiform bodies underlain by stockwork and feeder zones in highly altered volcanic rocks (Garcia Palomero, op. cit.). Hydrothermal alteration in the inner zone of the Corta Atalaya stockwork is characterized by intense leaching of Na and enrichment of Mg-K-Tl-Ba-Se-S. Alteration minerals are of the muscovite and chamosyte (chlorite) type. The outer zone shows leaching of K and lesser enrichment in Mg-Tl-Se-Sb; typical alteration minerals are celadonite-rich white mica and Fe-chamosyte (Leca & Leistel, 1993). Weathering of the original Cerro Colorado massive sulfide deposit produced a 70 m thick gossan consisting mainly of Fe-oxides and Fe-hydroxides which has been mined extensively for precious metals. Near the base of the 70 m thick gossan a lower zone of supergene enrichment contains Ag-jarosite.

Mine workings have produced enormous quantities of tailings and dumps, which are rich in pyrite and other sulfide and sulfate minerals. Heavy metals contained in the ores are released by oxidation and transported downstream in acidic waters where they precipitate together with Fe-hydrous oxides and Fe sulfates as coatings. Previous studies in the Tinto and Odiel river systems have documented the presence of localized heavy metal anomalies of As, Cd, Cu, Pb, Zn, Cr, and Hg in the fluvial, estuarine, and off-shore sediments (Nelson and Lamothe, 1993; Van Geen *et al.,* 1997).

HYMAP DATA PROCESSING AND INTERPRETATION

The HyMap airborne hyperspectral sensor records 128 contiguous 10 – 20 nm-wide spectral channels in the 0.40-2.5μm wavelength (Cocks *et al.,* 1999). During June 1999, a 10 km-long line of HyMap data was recorded over the Río Tinto district, with 8-m ground-resolution. The images cover the central mine area and a sector of the Río Tinto valley, which drains a large area of dumps and old mine works located south of the main deposits.

The HyMap radiance data were converted to reflectance using in situ spectral reflectance measurements of homogeneous ground sites. Fieldwork carried out during July 1999 resulted in acquisition of in situ reflectance spectra over mine dumps, tailings and a wide range of soil and rock exposed in the study area. Also, samples of these materials were taken for subsequent X-ray diffraction (XRD) and chemical analyses. In situ spectra were critical for calibrating the

HyMap data and as reference spectra during the data processing and analysis. Processing of the HyMap data included (1) use of a minimum-noise transformation (MNF) to reduce the noise and data volume; (2) production of a píxel purity image (PPI) for identifying end member image spectra; and (3) the use of full and partial spectral ranges of end member spectra as references in matched-filter processing (Boardman *et al.*, 1995). The resulting images were subsequently thresholded and overlaid on a single channel image which shows mineral abundance for each mineral considered. These mineral abundance images were evaluated in the field.

The selection of HyMap spectral bands for analysis depended on the mineral of interest and the wavelength position of the diagnostic spectral absorption feature. Fe minerals such as hematite, typically exhibit broad absorption features in the 0.4 to 1.0 micrometer region (Fig. 2), thus HyMap bands in this wavelength region were processed for identifying Fe minerals (Fig. 3A).

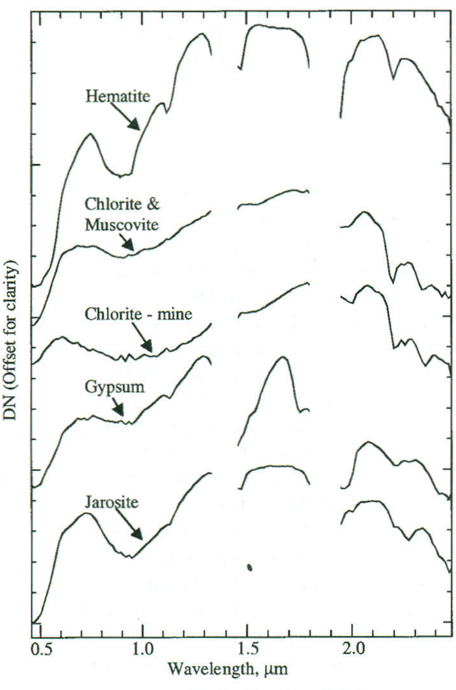

Figure 2. HyMap image spectra of several minerals mapped in figure 3A.

Chlorite with a 2.35μm absorption feature (Fig. 2; dark blue, Fig. 3A) is shown in the Cerro Colorado open-pit and associated dumps corresponding to altered chloritic slate. A 2.33μm absorption feature in chlorite (Fig. 2; cyan, Fig. 3A) appears to be associated with illite/smectite in andesite of the basic volcanic series (Fig. 2, Fig. 3B). AlOH$^-$ minerals such as muscovite (Fig. 2; red, Fig. 3B), is discerned in hydrothermally altered acid volcanic rocks outcropping in El Cerro del Aguila and dumps in Cerro Salomon, whereas illite/smectite (green, Fig. 3B) appears mainly in the slates of the Culm group in the north and in greywacke, slates and tuffs in the south (1, Fig. 3B).

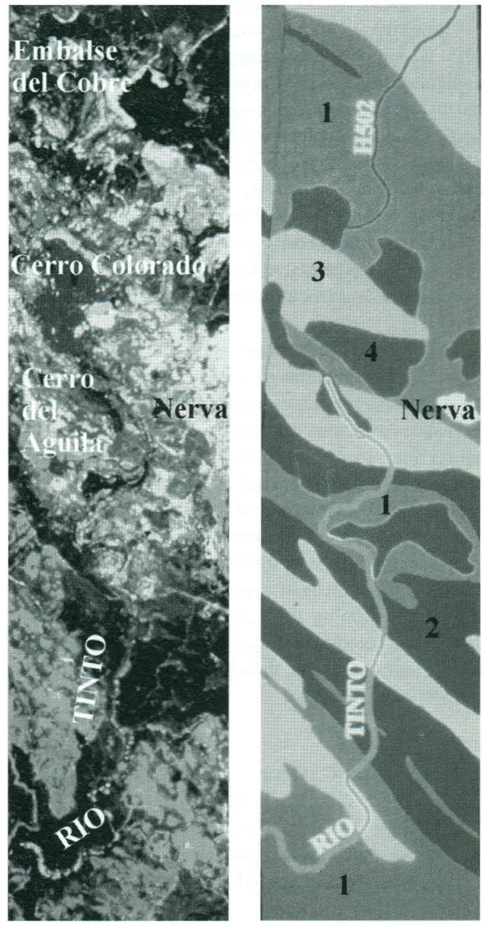

Figure 3. (A) Fractional abundance image and (B) generalized lithologic map of the Río Tinto mine area. Image color and dominant mineral: yellow, hematite/ goethite; dark blue, chlorite; cyan, chlorite+muscovite; red, muscovite; green, illite/smectite; orange, jarosite.

(Ver figura en color en la página 674)

Jarosite píxels appear commonly mixed with hematite and gypsum in altered rocks and in the Río Tinto alluvium (Fig. 2; orange, Fig. 3A), and hematite (Fig. 2; maroon, Fig. 3A) is widespread in dump materials commonly mixed with illite/smectite. Evaporite-bearing deposits (lavender, Fig. 3A), as well as hydrated sulfate minerals such as rozenite, copiapite, melanterite, appear mixed with hematite and gypsum (Fig. 2) in the river alluvium and the edges of mine ponds, which are at the north of the mine area.

DISCUSSION AND CONCLUSIONS

Several types of mine-waste materials were discerned with HyMap data, including dumps and tailings containing pyrite, jarosite, gypsum, copiapite, coquimbite, and several ferric-iron oxide minerals. Weathering of these materials and subsequent solubilization and precipitation has caused deposition of gypsum, copiapite, melanterite, and rozenite, as well as ferric-iron minerals in alluvium along the Río Tinto. Hydrothermal alteration mineral assemblages in the country rocks were also identified, including hydrothermal chlorite in the Cerro Colorado open pit mine and sericitic alteration zone around chloritic alteration.

Mine dumps and tailings in mine areas can generate important contamination of the watershed and ecosystem by dispersion of heavy metals throughout surficial drainage. Acid mine drainage is a major problem that affects areas located near to abandoned or inactive mines. The new hyperspectral imaging systems permits rapid, effective mapping of the secondary minerals distribution related to acid mine drainage. Hence, hyperspectral image analysis is a useful technique for assessing the sources of heavy metal pollution in mine sites and mapping the distribution of mine-waste products and polluted soils, as well as naturally occurring altered rocks and soils, throughout the mining districts and along the drainage.

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