Application of Imaging Spectrometer Data in Identifying Environmental Pollution Caused by Mining at Rodaquilar, Spain

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The Rodaquilar mining area in southern Spain has been mined for gold for an extensive period, most recently in the 1940s and 1950s. This activity has resulted in waste rock and tailings being dispersed from the mine workings down to a large tailings dump and then along a river valley eventually reaching the sea. This tailings dump material consists of a variety of ferruginous materials that often contain trace elements that are environmentally harmful and possibly toxic. These ferruginous materials have distinctive spectral features which make them amenable to detection and mapping by airborne imaging spectrometer data. The dispersion of the tailings material was studied using two semi-quantitative techniques, matched filtering and linear spectral unmixing and qualitative methods using band ratios and the variation in strength of spectral features. The distinct ferruginous mineral phases resolved by these methods were then compared to laboratory reference spectrum using qualitative analysis of the spectral profiles and two quantitative techniques, spectral angle mapping and cross correlogram spectral matching. The distribution of the ferruginous materials identified from the imaging spectrometer data supports the results of laboratory experiments on the dependence of the formation of iron species on their geochemical and physical situation. ©Elsevier Science Inc., 1999

INTRODUCTION

The release of trace metals into the environment by mining operations is of major health and environmental importance. Methods for assessing the spread of these pernicious, possibly toxic, elements have traditionally been geochemical, hydrologic, and geophysical in nature, and thus have required the collection of numerous samples followed by laboratory measurements. While remote sensing at optical wavelengths cannot directly detect trace metals, it can be used to map the minerals which host these metals. In recent years remote sensing has been successfully used to aid in this process (e.g., Fenstermaker and Miller, 1994; Swayze et al., 1996; Farrand, 1997, Farrand and Harsanyi, 1997). The advent of high quality airborne imaging spectrometer data provided by systems such as the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), (Chrien et al., 1996) enables new quantitative and qualitative techniques to be applied in assessing the environmental impact of mining activities.

This study demonstrates the use of imaging spectrometry data in determining different ferruginous species and in mapping the spread of tailings from a gold mining district. This study has utilized spectrum extracted from AVIRIS data collected over this site, and, after correlating these results with field spectrum and ground geochemical information, both qualitative and semi-quantitative estimates of the nature and dispersal of the tailings material were made.

The Study Area

This study is concerned with an area of gold mineralization at Rodaquilar in Southern Spain (Fig. 1). The epithermal gold mineralization at Rodaquilar is of the acid sulphate type (Arribas et al., 1989), hosted by rhyolitic ignimbrite deposits and domes within the caldera. There are economic ores of gold-alunite and lead-zinc-silver-gold veins, principally concentrated in ring and radial fractures around the western margin of the Cinto caldera (Transaccion mine), and alunite deposits in the Los Tol-
Figure 1. Location map of the study area, Rodaquilar (Southeastern Spain), with the mine workings and tailings dump marked.

los area at the north-eastern margin of the Rodaquilar caldera (Heald et al., 1987). The exploitation of these deposits has left an area composed of unvegetated open pit mine workings and tailings dumps (Figs. 1 and 2) surrounded by an area of hydrothermal alteration (argillic and siliceous), in volcanics of Tertiary age.

Field Studies

Rock and soil samples were collected from around the mining area as well as a number of field spectrum collected at the time of the data acquisition. Samples were collected from Rodaquilar and these were analysed mineralogically using XRD and their reflectance spectrum captured in the laboratory with the GER SIRIS spectroradiometer. The GER SIRIS has a spectral resolution of 2–6 nm, which means that ground spectrum can be related to the AVIRIS spectrum without losing any information. The XRD data indicate the existence of quartz, alunite, (natro-)jarosite, and, in smaller amounts, pyrophyllite, kaolinite and illite—minerals expected from prior knowledge of the alteration mapping. Other minor minerals detected with some confidence include calcite, gypsum, albite, muscovite, braunite (CaMn$_2$Si$_2$O$_7$), clino-clase (Cu$_2$(AsO$_4$)(OH)$_2$), nacrite (Al$_2$SiO$_2$(OH)$_4$), scorodite (FeAsO$_4$.2H$_2$O), variscite (AlPO$_4$.2H$_2$O), and brushite (CaFPO$_4$.2H$_2$O).

From the laboratory spectrum only alunite and jarosite spectral characteristics could be identified with confidence and correlated to the equivalent XRD results. Other spectrum are obviously complex mixtures. Another problem with identification is that, with the exception of scorodite, the other less common mineral species detected by XRD do not appear in reflectance spectral libraries such as that of Grove et al. (1992).

Characteristic Materials Associated with Mine Tailings

Trace elements can become aggregated in iron oxide and oxyhydroxide minerals (e.g., hematite, goethite, ferrihydrate, etc.) and/or mineraloids either through adsorption on the minerals surface or through direct incorporation into the mineral’s surface or through direct incorporation into the mineral structure (Schwertmann and Taylor, 1977).

Ferris et al. (1989) indicated that an abundance of poorly crystallized iron oxides are commonly produced in acid mine drainage sediments. In environments where high levels of Fe(III) are made available by the rapid oxidation of Fe(II), ferryhdyrite precipitation is favored. This poorly ordered hydrous compound is thermodynamically unstable and usually converts with time to more stable crystalline forms, such as hematite or goethite (Fischer and Schwertmann, 1975). Schwertmann and Murad (1983) showed that goethite and hematite form from ferrihydrate by two different and competitive mechanisms, goethite crystals form in solution from dissolved Fe(III) ions produced by the dissolution of ferrihydrate, whereas hematite forms through an internal dehydration and re-
arrangement within the ferrihydrite aggregates. Which end product predominates depends on the pH and the temperature of the system. Foreign ions and compounds also influence the nature of the reaction product and modify its crystal habit (Cornell et al., 1987). The conversion time for ferrihydrite increases dramatically with decreasing pH. However, even under the most adverse conditions 90% of the ferrihydrite had changed to goethite and hematite within 1000 days and at a pH of 3 the time of half conversion from ferrihydrite to goethite and hematite was approximately 300 days (Schwertmann and Murad, 1983).

Swayze et al. (1996) mapped acid-generating minerals produced from a gold, silver, lead, and zinc deposit at Leadville, Colorado. At Leadville the sulfide oxidation process is biologically driven along complex chemical pathways with feedback reactions that enhance the speed and magnitude of oxidation. Release of heavy metals is facilitated by sulfide oxidation, since many of the sulfides contain the heavy metals (e.g., Pb, As, Cd, Ag and Zn). The oxidation-weathering process produces low pH water in which the heavy metals dissolve as aqueous phases which are then transported by runoff into nearby streams. Secondary minerals, such as jarosite, ferrihydrite, schwertmannite, goethite, and hematite, are formed by sulfide oxidation or precipitation from metal-rich water. These secondary minerals are Fe-rich, and, as is shown in Figure 3, such minerals have unique reflectance characteristics in the visible and near-infrared portion of the spectrum (0.4–1.3 μm) and thus are highly amenable to detection and mapping in imaging spectrometer data. As the pH of the stream water increases, from dilution with higher pH sources, the secondary minerals precipitate out as stream bed coatings. Because the heavy minerals can substitute for Fe, they are also precipitated from solution as constituents of secondary minerals or as contaminants absorbed onto the surfaces of the secondary minerals. Subsequent pulses of low-pH water may dissolve the secondary minerals and remobilize the heavy metals and transfer them downstream.

**DATA AND IMAGE PROCESSING**

The remote sensing data primarily used in this study was from the AVIRIS imaging spectrometer. AVIRIS data was acquired over Rodaquilar under clear conditions at 13:37 on 15 July 1991 as part of a swath of five contiguous scenes by an ER-2 aircraft as part of the MAC-EUROPE'91 campaign. Contemporaneous Thematic Mapper Simulator (TMS) (11-channel) data were also collected together with infrared photography. Limited fieldwork was carried out around the time of the overflight involving collection of field spectrum at specific sites and the assessment of vegetation cover.

The AVIRIS consists of four separate spectrometers and the D-spectrometer that records the SWIR produced very noisy data over Rodaquilar. Signal-to-noise ratios for the first three spectrometers were good, averaging about 100 for bright targets and in the range 100–50 for dark targets. The signal-to-noise ratio for the
effects, only an apparent reflectance value can be retrieved. A number of techniques for retrieving apparent surface reflectance values for this data were used including the empirical line technique and a number of radiative transfer modeling methods. The application of these techniques is discussed fully in Ferrier and Wadge (1996) and Ferrier, (1997). When inspecting the spectra derived from the AVIRIS data, Figures 6 and 9, two wavelength regions, around 0.94 and 1.14 μm, can be shown to exhibit quite noisy spectral profiles. These artifacts are caused by errors in the conversion from radiance to apparent surface reflectance. These wavelength regions have very high atmospheric attenuation due to water vapor and hence are very sensitive to errors in the estimation of the total water path length. A major contribution to the error in estimating total water path length is the variation in the path length due to topographic effects. In this project the limited number of field survey sites meant that this effect could not be fully removed. However, outside these high attenuation wavelengths, the resultant effects on the spectral profiles are very limited.

Spectral Subsectioning and Noise Whitening

The AVIRIS scene covering the Rodaquilar mine was subsectioned to 400 samples by 400 lines to concentrate solely on the Rumba del Playazo River Valley. The data was also spectrally subsampled to the first 105 bands covering the 0.4–1.32 μm waverange. This resampled section was subjected to noise processing as suggested by Boardman et al. (1995) and Farrand and Harsanyi (1997). A minimum noise fraction (MNF) transform (Green et al., 1988) was applied which produces a set of principal component images ordered in terms of decreasing signal quality. By performing an inverse MNF transform utilizing only the significant (i.e., signal bearing) images, a full image cube can be reproduced in which the noise has a gaussian distribution and unit variance. By performing the forward and inverse MNF transforms on the apparent surface reflectance AVIRIS data, data cubes were produced that contained a lower noise component than the original data. The spectrum from these transformed image cubes could be directly compared against the reflectance spectrum that were measured in the field or laboratory.

Spectral Data Processing

The plot of the eigenvalues of the MNF transform indicates there are seven prominent eigenvalues (Fig. 4), which suggests there are seven or possibly eight visible–VNIR endmembers. The principal components determined by the MNF transform were plotted in both 2 and n dimensions using the Environment for the Visualisation of Images (ENVI) Version 2.0 (Research Systems, Inc., 1995) software package. The seventh MNF image was found to very clearly represent the tailings dump

Figure 3. Laboratory spectrum of hematite (OH-1A), goethite (OH-2A), and natrojarosite (SO-7A) from Grove et al. (1992). b) Laboratory spectrum of ferricydrite (GDS75), hematite (GSS27), and jarosite (GDS24) from USGS spectral library [in ENVI Version 2.0, Research Systems, Inc. (1995)].

D-spectrometer, however, was poor, averaging about 12 in the central part of the range (near 2.2 μm) but falling off to 5 or less at either limit for bright targets and staying below 5 for dark targets throughout the range. The effective loss of the SWIR data was a major setback for the primary aim of the Rodaquilar project which was the study of the alteration zones associated with the epithermal gold deposits at Rodaquilar. However, in this study it is of less importance as the variations in spectral profile in the visible and VNIR wavelengths are of greater interest.

Reduction to Apparent Surface Reflectance

The reflectance values retrieved from remotely sensed data are affected by many factors including the physical state of the surface and its orientation towards the Sun at the time of data acquisition. Therefore, even after the correction of the remotely sensed data for atmospheric
material. When the principal components from the MNF transform are plotted against each other, the tailings dump material is seen to form an extremely distinct spectral grouping (Fig. 5). A “pixel purity index” (PPI) was applied to the MNF image bands that contained any information. This algorithm (Boardmann et al., 1995) examines the n-dimensional data cloud (where n is the intrinsic dimensionality of the data) in a series of projections to find the most spectrally extreme pixels. Those pixels deemed “purest” were then examined using the n-dimensional visualizer in ENVI. Vertices in the n-dimensional data cloud(s) were extracted. The surface materials on the ground covered by these pixels could then be identified based on their visible and infrared reflectance spectrum. After this analysis eight endmembers were identified, sea, shade, live vegetation, tailings dump material1, tailings dump material2, mine material, stream material and country rock. The mean spectral signals from the four endmembers assumed to contain some ferruginous material are shown in Figure 6.

Spectral Analysis
In order to assess the extent and degree of the dispersion of the tailings dump material, a number of spectral analysis techniques have been applied ranging from purely visual, qualitative analysis to techniques employing various numerical algorithms. Even the analysis employing numerical techniques cannot be classified as quantitative analysis of the remote sensing data as this usually relates to concentration. This attribute is not readily obtainable from remote sensing data because the length, or the distance through the surface material traversed by a photon is not obtainable. The techniques employed here, matched filter and linear unmixing, will yield different estimates of mean percent cover and are therefore most appropriately classed as semiquantitative.
Playazo to within 600 m of the beach at El Playazo. The variations in the AVIRIS-derived spectral profile of this tailings dump material along the Rumbla del Playazo are shown in Figure 9. It can be seen that there is a reduction in the height of the local reflectivity maximum from approximately 70% at position 1 in the tailings dump to approximately 50% at position 8 about 600 m from the beach. The absorption edges, shoulders, and minima in the spectral profiles remains quite distinct up to position 8. From position 8 to position 10 the absorption features in the spectral profiles are not really identifiable. Looking at the spectrum from position 1 to position 8, it is quite clear that the tailings dump material is being transported at least as far as position 8. The diminution of the spectral profile is at least partly due to a decrease in the amount of tailings dump material in the bed of the Rumbla del Playazo. From position 8 to position 10 (at the beach) the tailings dump material either disappears or is being obscured.

**Qualitative Analysis of Dispersion**

The spectral profile of the tailings dump material (Fig. 7) shows an absorption edge at 0.54 μm, a reflectance shoulder at 0.63 μm, a local reflectivity maximum at 0.74 μm, a band minimum at 0.85 μm, and another reflectance shoulder at approximately 1.04 μm. A qualitative impression of the dispersion of this tailings dump material can be obtained by dividing the AVIRIS band centered at 0.74 μm by the AVIRIS band centered at 0.85 μm. The resulting image (Fig. 8) shows very clearly the tailings dump material extending down the Rumbla del Playazo to within 600 m of the beach at El Playazo. The variations in the AVIRIS-derived spectral profile of this tailings dump material along the Rumbla del Playazo are shown in Figure 9. It can be seen that there is a reduction in the height of the local reflectivity maximum from approximately 70% at position 1 in the tailings dump to approximately 50% at position 8 about 600 m from the beach. The absorption edges, shoulders, and minima in the spectral profiles remains quite distinct up to position 8. From position 8 to position 10 the absorption features in the spectral profiles are not really identifiable. Looking at the spectrum from position 1 to position 8, it is quite clear that the tailings dump material is being transported at least as far as position 8. The diminution of the spectral profile is at least partly due to a decrease in the amount of tailings dump material in the bed of the Rumbla del Playazo. From position 8 to position 10 (at the beach) the tailings dump material either disappears or is being obscured.

**Semi-Quantitative Analysis of Dispersion**

**Matched Filtering**

Matched filtering maximizes the response of a known endmember and suppresses the response of the composite unknown background, thus "matching" the known signature (Harsanyi and Chang, 1994). Matched filtering performs a partial unmixing finding the abundances of user-defined endmembers. It provides a rapid means of detecting specific minerals based on matches to specific library or image endmember spectrum and does not re-
Figure 9a. Map of the locations of sample points for the AVIRIS-derived spectral profiles along the Rumbla del Playazo.

Figure 9b. AVIRIS-derived spectral profiles from sample points 1–3 along the Rumbla del Playazo (see Fig. 9a), no offset along the $y$-axis.

Figure 9c. AVIRIS-derived spectral profiles from sample points 4–10 along the Rumbla del Playazo (see Fig. 9a), with a 20% offset along the $y$-axis for each spectral profile.
The results of the unmixing analysis are generally very good (Fig. 11). The pixels with the poorest result (0.0) are displayed as pure white whereas the pixels with the highest result (1.0) are displayed as pure black. The contour lines (see Fig. 1) are also in black and underlie the unmixing results. The first endmember (tailings dump material 1) is mainly concentrated in the large tailings dump with only a few occurrences located along the Rumbla del Playazo. The second endmember (tailings dump material 2) is mainly concentrated along the Rumbla del Playazo, showing a variation in concentration. It also appears on the beach at La Playazo. The third endmember (mine material) has a very limited but clear outcrop located in the mine workings. The fourth endmember (stream material) shows a limited, linear distribution most clearly southwest of the main tailings dump. The fifth endmember shows very clearly the distribution of the live vegetation. Of most interest is its patchy distribution along the Rumbla del Playazo and especially the large patches of vegetation located within 600 m of the beach at El Playazo. While all the spectra shown in Figure 8 show some minor influence of vegetation (a small red edge near 0.7 μm) there is not a significant increase in the vegetation influence as the Rumbla nears the beach.

Figure 10. The results of the match filtering along the Rumbla del Playazo.

The mean spectrum from a region of interest of 100 pixels from the tailings dump was calculated and used as the endmember in the matched filtering. The scores of the match filter in the Rumbla del Playazo area (Fig. 10) range from 0.2 to 0.9 and vary quite rapidly on a pixel-to-pixel basis. The poorest results (0.0) are displayed as pure white while the best results (1.0) are displayed as pure black. The contour lines (see Fig. 1) are also in black and underlie the match filter results. The results clearly show the tailings dump, the mine workings, and a trail of tailings dump material extending down the Rumbla del Playazo, finally stopping about 600 m from the beach at El Playazo.

Linear Spectral Unmixing
Linear spectral unmixing is a means of determining the relative abundances of materials depicted in multispectral imagery based on the materials spectral characteristics. The reflectance at each pixel of the image is assumed to be a linear combination of the reflectance of each material (or endmember) present within the pixel. The number of endmembers must be no more than \( n + 1 \), where \( n \) is the number of spectral bands (Adams et al., 1993; Sabol et al., 1992). After identifying these types or endmembers from the image or spectral library, the appropriate proportional mixture to fit the spectrum of each pixel is computed using least squares techniques (e.g., Settle and Drake, 1993).

Spectral unmixing results are highly dependent on the input endmembers. The endmembers defined after inspecting the MNF transform images in two and more dimensions and also the results of the pixel purity index analysis indicated eight spectrally distinct endmembers in the visible-VNIR wavebands.

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The reduction in the contribution of the tailings material to the overall spectral signal along the last 600 m of the Rumbla could be the result of a number of factors. If increased vegetation was masking the spectral signature of the tailings material, then there should be more evidence of vegetation spectral features in the profiles nearest the beach. It is possible that dead vegetation or plant litter might be more abundant closer to the beach, and this could be helping to mask the spectral response of the tailings material. More probably, there is more country rock/gravel mixing with the tailings material the further one gets from the mine causing a diminution of the spectral response of the tailings material. The spectral profiles displayed in Figure 9 are the pixels displaying the strongest contribution from the tailings material at each point along the Rumbla.

RESULTS

Discussion of Endmembers
Of the eight endmembers defined above, four were thought likely to contain some ferruginous material. In order to gain further insight into the processes occurring, it is necessary to try to identify these four endmembers using qualitative and quantitative techniques. These endmembers were initially compared to laboratory spectrum from the JPL and USGS spectral libraries. Spectrum for the most probable mineral phases: hematite (OH-1A), goethite (OH-2A), jarosite (SO-7A), and ferricydrite (USGS) are shown in Figure 3.
Figure 11. The results of the spectral unmixing analysis: a) tailings dump material1, b) tailings dump material2, c) mine material, d) stream material, and e) live vegetation.

Qualitative Analysis of Endmember Types
The main tailings dump material (tailings dump material1) has an absorption edge at approximately 0.54 μm, a shoulder at 0.63 μm, a local reflectivity maximum at 0.74 μm, a band minimum at 0.85 μm, and another reflectance shoulder at 1.04 μm. These features plus the general shape of the spectrum correspond very strongly with the hematite (OH-1A) reference spectrum and indicate that it is very hematite-rich.

The second material associated with the main tailings dump (tailings dump material2) appears spectrally quite similar to the tailings dump material1 except for but a general reduction in the intensity of the absorption features and the location of the absorption shoulder at approximately 0.59–0.6 μm. This material is located around the rim of the main tailings dump in a few patches, at some points along the Rumbla del Playazo and on the beach at La Playazo. These features again
correspond strongly with the hematite reference spectrum (OH-1A) but also suggests either some contamination or diminution in the tailings dump material.

The stream material endmember spectral profile is flatter than the first two endmembers with an absorption edge at 0.54 μm, two local reflectivity maxima at 0.57 μm and 0.76 μm and two indistinct band minima at approximately 0.66 μm and 0.87–0.89 μm.

The mine material endmember has an absorption edge at approximately 0.54 μm, a shoulder at 0.57 μm, a local reflectivity maximum at approximately 0.73–0.75 μm, and a band minimum at approximately 0.85–0.86 μm. These features strongly indicate the presence of hematite and suggest the presence of another ferruginous species.

Quantitative Analysis of Endmember Types
To assist in the determination of these endmembers two quantitative techniques have been applied to this spectral analysis. The first technique was the spectral angle mapper (Kruse et al., 1993) which determines spectral similarity between the image endmembers and the laboratory spectrum. The lower the spectral angle between two spectrum, the more similar they are. The main tailings dump material (tailings dump material1) was very similar to the hematite library spectrum (OH-1A) with the best match of 0.039 and a mean of 0.054. The second material associated with the tailings dump (tailings dump material2) had its best fit of 0.042 with goethite (OH-2A) whereas the best fit for the mine material was 0.052 with jarosite (SO-7A). Ferrihydrite, from the USGS spectral library, gave a poor match with all these endmembers.

The second technique was a cross-correlogram spectral matching approach (Van der Meer and Bakker, 1997). A cross-correlogram is constructed by calculating the cross-correlation coefficient between a test spectrum (a pixel spectrum) and a reference spectrum (a laboratory or endmember pixel) at different match positions. By convention, the reference spectrum is moved and referred to a negative match position when shifting toward a longer wavelength. Thus match position 1 means that we are calculating the cross correlation between the test spectrum and the reference spectrum in which all channels have been shifted by one channel position number to the lower end of the spectrum. The cross correlation, at each match position, \( m \), is equivalent to the linear correlation coefficient and is defined as the ratio of the covariance to the product of the sum of the standard deviations. If we denote the test and reference spectrum as \( \lambda_t \) and \( \lambda_r \), respectively, and define \( n \) as the number of overlapping positions, the cross correlation for match position \( m \) can be calculated as

\[
    r_m = \frac{\sum \lambda_t \lambda_r - \sum \lambda_t \sum \lambda_r}{\sqrt{n \sum \lambda_t^2 - (\sum \lambda_t)^2} \sqrt{n \sum \lambda_r^2 - (\sum \lambda_r)^2}}
\]

The skewness of the pixel correlogram was calculated and rescaled between 0 and 1, taking the absolute value of the sum of the correlation at \( m=4 \) and \( m=-4 \) divided by 2 and subtracted from 1 as

\[
    \text{skewness} = 1 - \frac{|r_m=4 - r_m=-4|}{2}
\]

In this case the mean spectrum for the four ferruginous endmembers were used as inputs into the cross correlogram spectral matching and compared to four reference laboratory spectrum, hematite (OH-1A), goethite (OH-2A), natrojarosite (SO-7A), and ferrihydrite (GDS75). The cross-correlogram provides information for discriminating between mineral species, specifically the cross correlation at \( m=0 \), the shape of the correlogram and the position of the peak of the function. The results of spectral matching for the four endmembers are shown in Figures 12 and Table 1. The closer the match of the test spectra to the reference one will result in the cross-correlogram have a match of 1.0 at \( m=0 \) and a symmetrical curve at match positions moving away from \( m=0 \).

The cross-correlogram for tailings material1 shows hematite with the highest correlation at match position at \( m=0 \) and the most asymmetric curve, with a skewness of 0.995. The other reference spectra have much lower correlations at \( m=0 \) and much more skewed spectral match curves. The cross correlogram for tailings material2 looks very similar to tailings material1 with hematite having the highest correlation at match position \( m=0 \). However the correlation is lower than for tailings material1, the goethite curve has a higher correlation value and the skewness value for goethite and hematite are identical. The cross-correlogram for the mine material is more complicated with goethite, jarosite, and hematite having quite similar correlation values at \( m=0 \). The skewness values are also reasonably similar. The cross correlogram for the stream material shows goethite with by far the highest correlation value at \( m=0 \) and with the highest skewness factor.

The results from both the qualitative and quantitative approaches to endmember identification is that tailings dump material1 band minimum and shoulder near 0.85 μm and 0.63 μm corresponds to the \(^5A_1 \rightarrow ^7T_1 \) and \(^5A_1 \rightarrow ^7T_2 \) transitions, respectively (Morris et al., 1985). These features correspond exceptionally strongly to the hematite spectrum and can therefore be classified as such. Tailings dump material2 is in some aspects spectrally quite similar to tailings dump material1, which suggests it is mineralogically quite similar but has one or more additional features which distinguishes it from the other tailings dump material. This could be a combination of grain-size or contamination, by jarosite or goethite, causing reduction in hematitic signal or possibly even some chemical reaction changing the hematitic material into another ferruginous phase. The mine material again has again strong hematitic spectrum features but in addition has features suggesting the presence of jarosite. The stream material is located away from the main tailings dump mainly along streams. It has quite a dis-
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Figure 12. a) Cross-correlation plots for the tailings dump material1 endmember against hematite (hem), goethite (goeth), ferrihydrite (ferr), and natro-jarosite (njar_mod). b) Cross-correlation plots for the tailings dump material2 endmember against hematite (hem), goethite (goeth), ferrihydrite (ferr), and natro-jarosite (njar_mod). c) Cross-correlation plots for the stream material endmember against hematite (end2_hem), goethite (end2_goeth), ferrihydrite (end2_ferr), and natro-jarosite (end2_njar). d) Cross-correlation plots for the mine material endmember against hematite (hem), goethite (goeth), ferrihydrite (ferr), and jarosite (jar).

tinct spectral profile which strongly suggests it is in part made up of goethite.

CONCLUSIONS

The major phase of mining activity at Rodaquilar ended in the late 1950s with only very minor activity at the site since then. The unvegetated open pit mine workings and tailings dumps have therefore remained undisturbed for almost 40 years. Metastable iron species such as ferrihydrite were found to be completely absent, and instead there was a widespread distribution of very well-formed hematite and, to a much lesser extent, goethite material. The results of Schwertmann and Murad (1983) experiments support very strongly the hypothesis that enough time has elapsed to allow the full conversion of the iron
species from their metastable form (ferrihydrite) to stable forms (hematite and goethite).

The results of Schwertmann and Murad (1983) experiments also help explain the distribution of the iron species. The finding that hematite is formed from ferrihydrite through an internal dehydration and rearrangement within the ferrihydrite aggregates strongly supports the hypothesis that the concentration of the hematite material in the main tailings dump was due to this process. The distribution of the goethite along narrow stream beds also corresponds strongly to their findings that goethite is produced from ferrihydrite that has been dissolved into Fe(III) ions.

The association of jarosite in the mine workings with secondary hematite and goethite further down the dispersion path is similar to that described by Swazy et al. (1996). They found that the jarosite and jarosite-goethite mine-waste areas had a high acid-generating capacity and are surface point sources for acid water and heavy metals. Areas covered by goethite and hematite can still contain heavy minerals (adsorbed on or as components of the secondary minerals), but they will not be mobile in the absence of low pH water, normally found in the jarosite-rich areas.

In this article it has been demonstrated that the nature of the ferruginous species and consequently the dispersion of the contaminated material can be obtained from imaging spectrometer data. This study has shown that the tailings material, containing pernicious, possibly toxic, trace material, has been dispersed all the way from the mine workings, through the main tailings dump and for approximately 3.5 km along the Rumba del Playazo to the beach at El Playazo.

Mining activities of the scale as those conducted in and around Rodaquilar significantly affect the surrounding environment. Ineffective laws relating to the use of particular chemicals and the proper handling of waste material in the past has lead to significant environmental impact. Therefore, the escape of this contaminated material from the large tailings dump along the Rumba del Playazo all the way to the beach at La Playazo is not unexpected.

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