(3) REMOTE SENSING FOR WASTE CHARACTERISATION

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Introduction

Remote Sensing plays an important role for waste characterisation due to its capabilities of discrimination or identification of materials. The synoptic perspective of overhead sensors, screening large areas and providing a spectral analysis at each pixel of the image, makes it a cost-effective, non-invasive and relatively rapid technique when compared to traditional sampling methods.

The extraction of information from the images is dependent upon the characteristics of the sensors, particularly concerning the spectral and spatial resolution, and afterwards of the algorithms used on processing. Thus, different sensors provide more or less detailed spectral data over the S. Domingos mining site (Fig. 1), which can be processed for delineation of waste morphology or establishment of its hazardous character. In this, multispectral sensors depict much lower spectral resolution (Fig. 1a), when compared to Imaging Spectroscopy (IS) or hyperspectral sensors, with tens or hundreds of bands either of radiance or corrected to reflectance (Fig.1.b). The IS, allowing the extraction of information at mineralogical and chemical level, are particularly suitable for waste characterisation using diverse processing strategies.

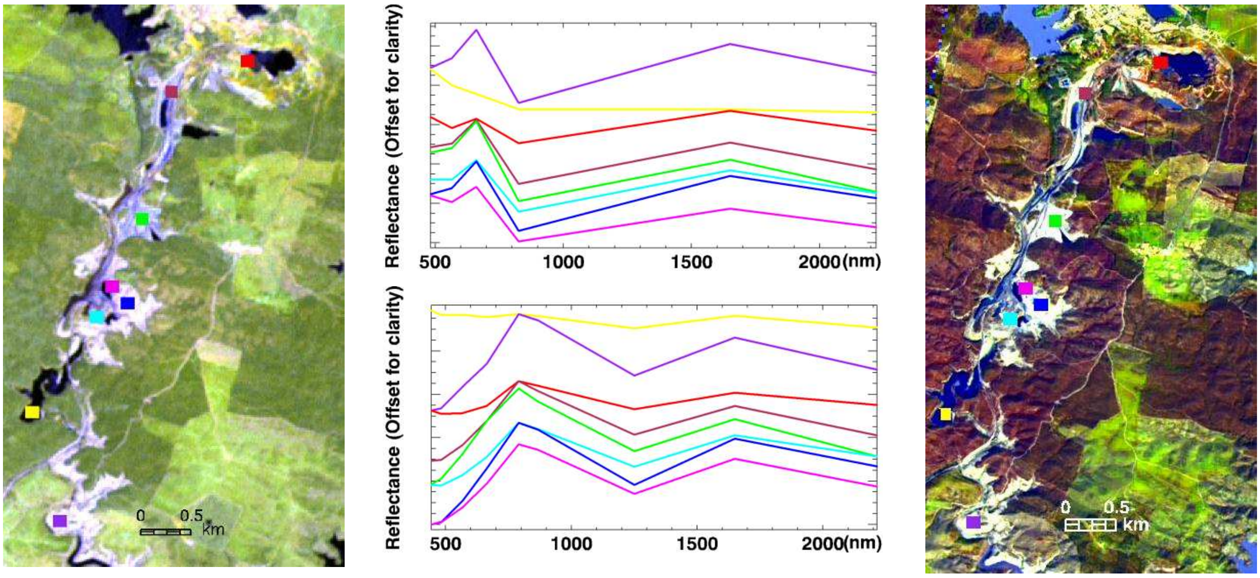
On waste characterisation, a key-issue is the assessment of the degree of hazardous in order to remediate or isolate the most dangerous areas. Hazardous waste can also be naturally occurring substances, such as heavy metals like lead and mercury that are brought into much higher than normal exposure concentrations by anthropogenic processes (Sloenecker et al. 2010). In the case of S. Domingos mine, the waste materials of several types are estimated to be 14.7 M m^3 accumulated to thicknesses varying very irregularly from 14 m near the open pit to less than 1 m at the locations furthest downstream (Matos, 2004; Matos and Martins, 2006). These materials may contain high acid generating potential, and the acidic waters can subsequently release the hazardous elements enclosed in significant quantities into the environment. Contents of hazardous elements on soils, sediments and waste materials, can reach maximum values of As=15,900 mg kg^{-1}, Pb=32,170 mg kg^{-1}, Hg=9300 mg kg^{-1}, Sb=5640 mg kg^{-1}, Zn=14,850 mg kg^{-1}, S=8 mg g^{-1} and Fe=400 mg g^{-1}, while pH measured is as low as 1.6 in Achada do Gamo (Tavares et al., 2008). The AMD is generally associated to high level pollutant content of the waters, decreasing with increasing pH values.

For the assessment of waste materials using IS, with the HyMap™ sensor (Fig.1b), two types of mapping were undertaken to assess the AMD (detailed in Quental et al., 2011): I) one is based on a full pixel approach using a similarity measure algorithm (SAM, Kruse et al., 1993) comparing the image with the in situ field spectra, generating a land cover with detailed spectral resolution, and II) another with the same algorithm but using as input multi-source spectra of different origins, i.e. image, field and mineralogical spectral libraries (Clark et al., 2007) of high correlation:

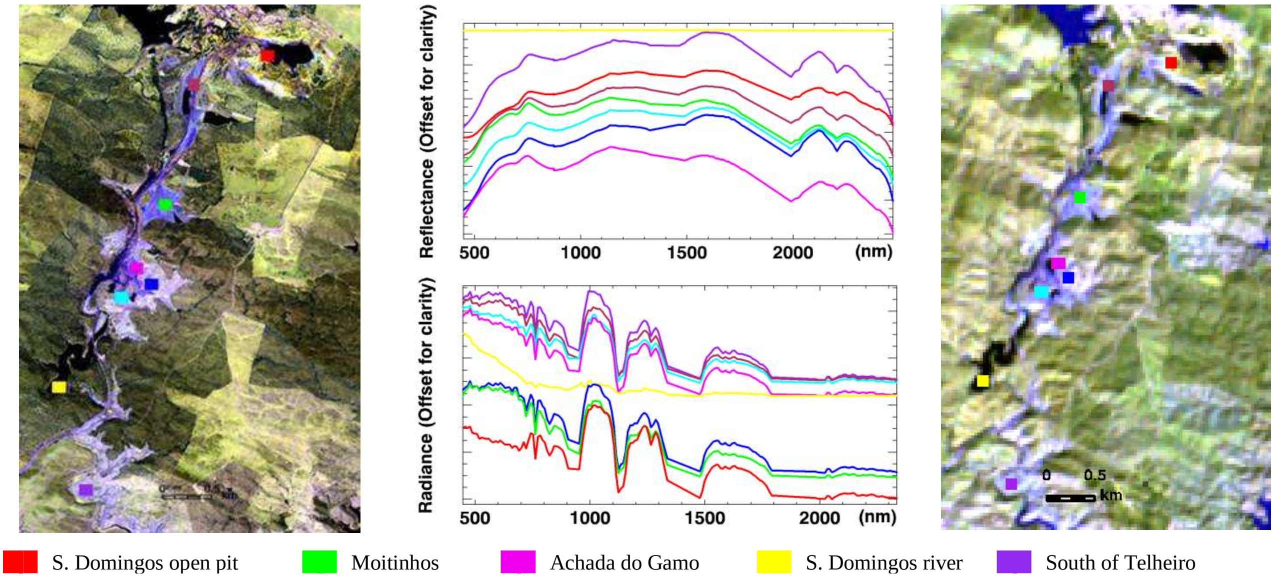
I) **AMD waste materials map**

The spatial pattern depicted by the spectral signatures of field materials, collected with an ASDFieldSpecPro spectroradiometer, from the surrounding area of the S. Domingos open pit to the Pomarão harbour is detailed in ten classes (Fig.2). Southward from the Telheiro area (Fig. 1) the railway track used to transport the ore is highlighted by the dispersion of mining waste materials. The classes obtained, with an average statistical parameter coefficient of variation (CV) of 0.29, indicating low data variability and probably the absence of anomalous data, are also compared with other data type, i.e. waste field map, and mineralogy determined from XRD diffraction of soils clay fraction.

The most relevant class for the AMD detection is the *mixed sulphur materials*, classified as such due to visible native S within the samples measured. This class is spread near or inside the acidic dams and S. Domingos river, and also on sulphide waste piles.



a) Satellite multispectral images. Left and upper centre: Landsat ETM+, sharpened image captured on 25/05/2003 (7 bands, pixel-15 m). Right and lower centre: EO-1/ALI sharpened captured on 06/02/2010. (9 bands, pixel-10m). Source: NASA.



b) Imaging spectroscopy or hyperspectral images. Left and upper centre: Hymap™, airborne, captured on 21/08/2000 (126 bands, pixel-4.1m) Source: HyVista Corporation. Right and lower centre: EO-1/HYPERION, spaceborne, captured on 06/02/2010 (149 calibrated bands, pixel-30m). Source: NASA.

Fig. 1 Images and equivalent average spectral profiles of coloured areas of targets for the S. Domingos mining area.

The designation *contaminated* on two of the classes' reports to the fact that geochemical analysis of the materials measured indicates high content of As, Hg, Pb, Sb and S (Tavares et al., 2008; 2009).

Despite the results obtained and consistent results comparing with data obtained by other analytic methods than spectral data, IS presents some challenges concerning classical validation methods of mapping which are not easily dealt with. One of the issues is related to the fact that IS may map the environment with greater detail and accuracy than the one that can be obtained by field crews or maps produced by other methods than Remote Sensing (Jacquez et al., 2002; Aspinall et al., 2002; Foody, 2008). Also, this AMD waste materials map has another issue concerning the AMD potential that is not hierarchically defined to other classes than "*mixed sulphur materials*", representing this one the lowest value of the wastes pH. However, the next upper degree of the pH is difficult to assign to another class (Fig. 2).

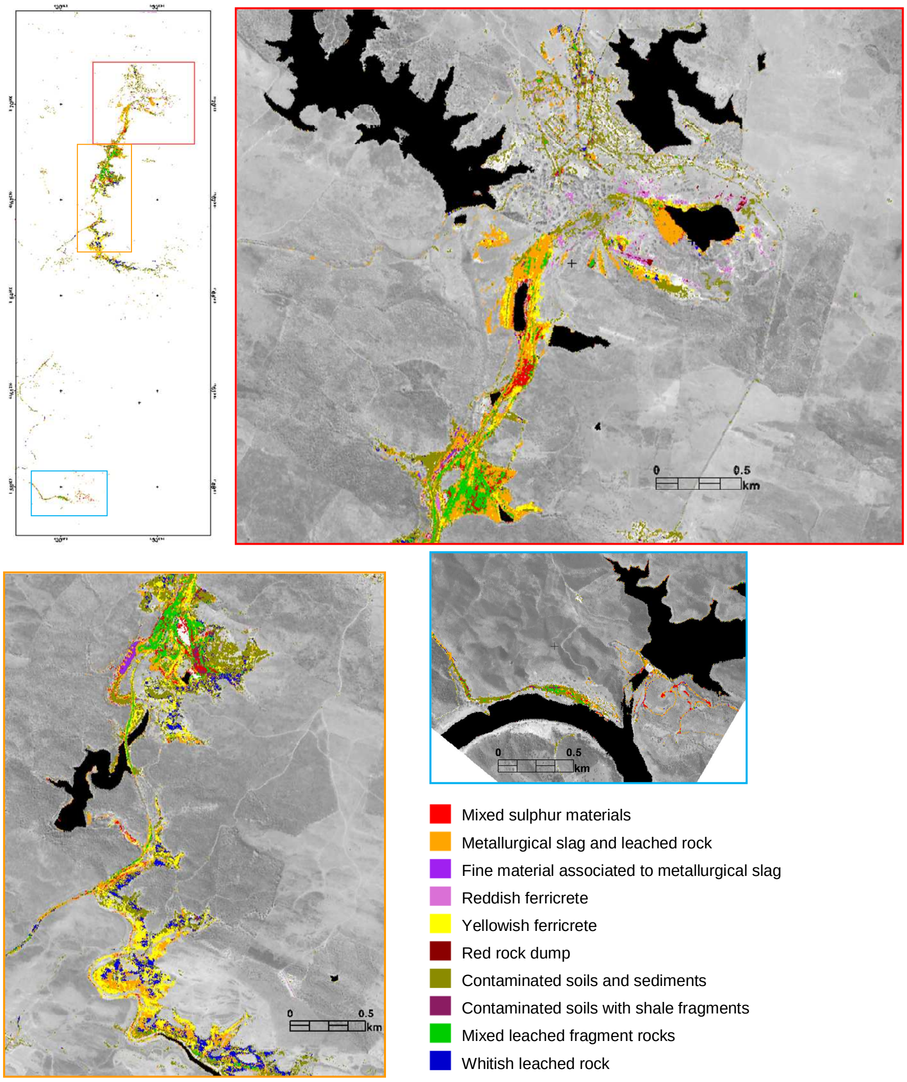


Fig. 2 Map of AMD waste materials (adapted after Quental & Brito, 2002) based on field spectra and using SAM (in Quental et al., 2011). Upper left-general scheme of the rectangle detailed maps, red-open pit, orange-Achada and Telheiro and blue-Pomarão harbour.

Although the AMD waste materials map depicts a global land cover with detailed "chemical" information related to the mining framework, it lacks quantitative information concerning the input field spectra or when exists reports to a different data type such as chemical or XRD analysis.

Thus, another methodology was developed as a contribution to answer part of IS validation issues, and also to improve the knowledge of the spectra as input algorithm to map.

The results are shown below.

II) AMD correlation minerals map (low pH minerals map)

The methodology relies on multi-source spectra that are also multi-scale spectra: mineralogical spectral libraries (Clark et al., 2007), field spectra and image derived endmembers using automatic procedures. To establish a quantitative link among them on a spectral basis, at the same wavelength range, the Pearson correlation matrix assigns mineralogical information to unknown spectra. This works as a spectra selector, using only spectra of high correlation (≥0.9) of our target of interest, i.e. minerals associated to AMD, and also that present high correlations among them. The selected field spectra are used to generate a map using SAM and the image derived endmembers generate another map. The field spectra and image derived endmembers maps are intersected on a pixel basis assigned to the mineralogical assemblages of high correlation. The final map is depicted in Fig.3.

The most relevant class is the copiapite (coquimbite)(alunite), in fact isolated spectrally. The assemblages of copiapite-coquimbite minerals are usually considered as typical of environments with pH≤3. The presence of these efflorescent salts has been reported at this test site, at Achada do Gamo , during the dry summer season (Abreu et al., 2010), and also in a similar environment within Iberian Pyrite Belt, typical of the banks of the stream affected by AMD (Ferreira da Silva et al., 2009).

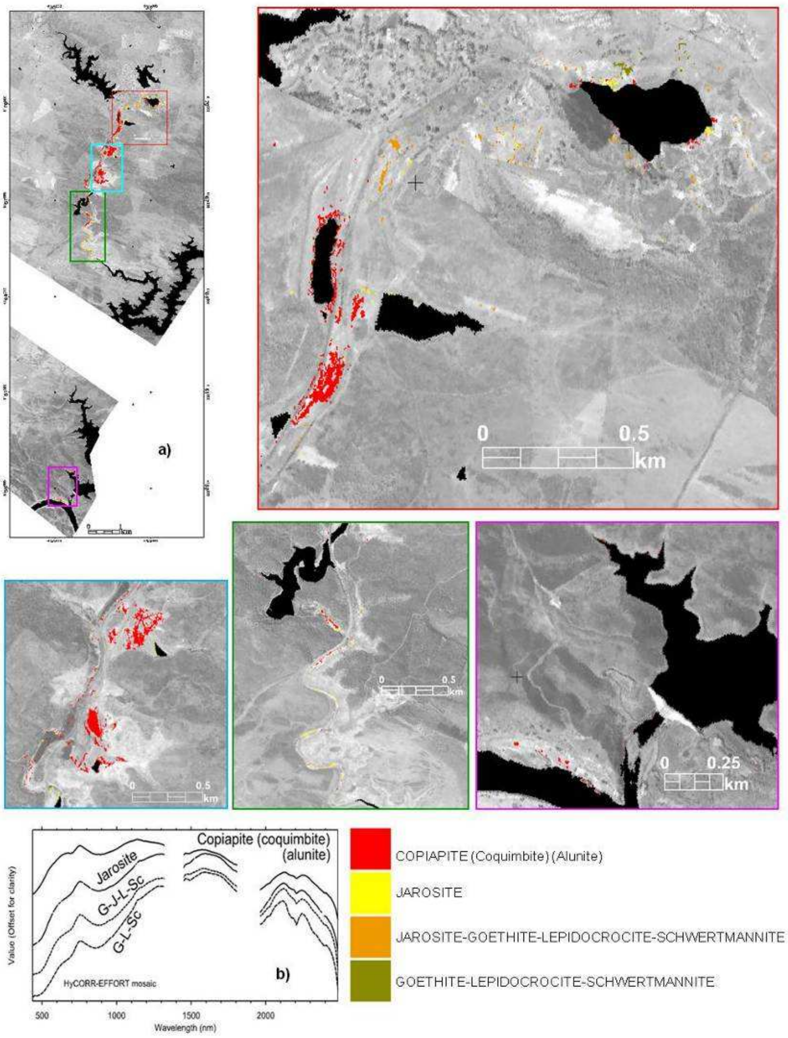


Fig. 3 Mineralogical correlation map ≥0.9 related to AMD. Assemblages of copiapite-coquimbite are typical of pH <3. Upper left: scheme of the detailed maps; b) Average values of spectra of the classes, lower left (in Quental et al., 2011).

The class copiapite (coquimbite) (alunite) occurs near the open pit close to finely crushed sulphide ore and downwards following the railway line and surrounding acidic dams, and on areas of more acidic wastes such as sulphide piles and cementation tanks N of Achada do Gamo. Downstream of Telheiro, this class follows the S. Domingos river and borders the stream until the Chança river. Similarly this also occurs at the Pomarão harbour. This pattern is spatially related to the jarosite class, when not isolated on some areas. The class goethite jarosite-lepidocrocite-schwertmannite (G-J-L-Sc) is mainly spread over the village, possibly indicating a more heterogeneous conditions of precipitation and mixtures of materials by remobilization, whilst the class goethite-lepidocrociteschwertmannite (G-L-Sc) appears N of the open pit apparently more stable with iron secondary minerals at higher pH environment, possibly connected to the geological framework. This northern part of the open pit is occupied by gossan materials, metavolcanic rocks and shale piles (Matos, 2004).

Final Remarks

The two maps I) and II) obtained through different methods are compared highlighting the advantages of the latter when mapping AMD related areas, by adding a correlation level, thus minimizing uncertainty and adding mineralogical knowledge to unknown spectra.

It's worth noticing the extremely favourable conditions for the use of Remote Sensing tools at the S. Domingos mining site, a paradigmatic example of AMD. The lack of vegetation allows the direct mapping using spectroscopy at several levels, including in situ field measurements spectra that highlight further knowledge not detectable at image scale when using correlation with mineralogical spectral libraries. This includes, e.g., the detection of jaroisite containing Pb (Clark et al., 2007), which may contribute for the comprehension of the metals cycling controlled by the dry and wet periods. Additionally, the mineralogical assemblages defined spectrally are different collected in these two periods (Quental et al., 2011a; b).

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