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Using multiple spectral feature analysis for quantitative pH mapping in a mining environment

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ABSTRACT

The pH is one of the major chemical parameters affecting the results of remediation programs carried out at abandoned mines and dumps and one of the major parameters controlling heavy metal mobilization and speciation. This study is concerned with testing the feasibility of estimating surface pH on the basis of airborne hyperspectral (HS) data (HyMap). The work was carried on the Sokolov lignite mine, as it represents a site with extreme material heterogeneity and high pH gradients. First, a geochemical conceptual model of the site was defined. Pyrite, jarosite or lignite were the diagnostic minerals of very low pH (<3.0), jarosite in association with goethite indicated increased pH (3.0–6.5) and goethite alone characterized nearly neutral or higher pH (>6.5). It was found that these minerals have absorption feature parameters which are common for both forms, individual minerals as well as parts of the mixtures, while the shift to longer wavelengths of the absorption maximum centered between 0.90 and 1.00 μm is the main parameter that allows differentiation among the ferric minerals. The multi range spectral feature fitting (MRSFF) technique was employed to map the defined end-members indicating certain pH ranges in the HS image datasets. This technique was found to be sensitive enough to assess differences in the desired spectral parameters (e.g., absorption shape, depth and indirectly maximum absorption wavelength position). Furthermore, the regression model using the fit images, the results of MRSFF, as inputs was constructed ($R^2 = 0.61$, $Rv^2 = 0.76$) to estimate the surface pH. This study represents one of the few approaches employing image spectroscopy for quantitative pH modeling in a mining environment and the achieved results demonstrate the potential application of hyperspectral remote sensing as an efficient method for environmental monitoring.

1. Introduction

Mining activities, both underground and open cast mining, are still associated with many environmental problems such as Acid Mine Drainage (AMD) (Akcil and Koldas, 2006), generation of large quantities of toxic substances (Kemper and Sommer, 2002) and consequent release of heavy metals into the environment (Gomes and Favas, 2006). As AMD can severely contaminate surface and groundwater, as well as soils, these anthropogenic activities can have serious human health and ecological implications (Grimalt et al., 1999; Grimalt and MacPherson, 1999) if the mines are not monitored and the necessary environmental treatment is not in place.

AMD release from mine waste rock, tailings and mine structures, such as pits and underground workings, is primarily a function of the mineralogy of local rock material (mainly secondary minerals associated with sulfide-bearing material) and the availability of water and oxygen. The typical AMD pattern leads to accumulation of Fe sulfates, oxy-hydroxides and oxides in a spatial and temporal sequence that represents the buffering of an acidic solution as it moves away from its source (Montero et al., 2005; Swayze et al., 2000). Therefore, these minerals can serve as pH indicators (indicative minerals). Because mineralogy and the other factors affecting AMD formation are highly variable within a site as well as from site-to-site, predicting the potential for AMD using conventional laboratory analysis can be exceedingly challenging and

Abbreviations: AMD, acid mine drainage; AOT, atmospheric optical thickness; CR, continuum removal; FWHM, full-width half-maximum; HCRF, hemispherical-conical reflectance factor; IS, image spectroscopy; LSU, linear spectral unmixing; MNF, minimum noise fraction transformation; MRSFF, multi range spectral feature fitting; MTMF, mixture-tuned matched filtering; PLSR, partial least square regression; PPI, pixel purity index; R^2, coefficient of determination (training dataset); Rv^2, coefficient of determination (validation dataset); Rad/Ref, at-sensor radiance-to-reflectance ratio; RRDF, radiance-to-reflectance difference factor; SAM, spectral angle mapper; SFF, spectral feature fitting; SMA, spectral mixture analysis; SVC, supervised vicarious calibration; SWIR, short-wave infrared; VNIR, visible near infrared; WV, water vapor content; XRD, X-Ray diffraction.

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costly. However, modern remote sensing has become a novel tool, not only for detecting and quantifying geological materials (Plaza et al., 2009; Van der Meer et al., 2012), but also for monitoring dynamic processes and induced changes in physical/chemical properties (Ben-Dor et al., 2009; Chabrillat et al., 2002; Escribano et al., 2010; Haubrock et al., 2008; Kokaly et al., 2003).

In a mining environment, the use of multispectral imagery has been effectively used to monitor environmental impacts (De Morais et al., 2012; He et al., 2009; Khalifa and Arnous, 2012; Matějíček and Kopačková, 2010) as well as to detect AMD generating material (Kopačková et al., 2012a; Robbins et al., 2000). However, the low spectral resolution of multispectral imagery is a major limitation. On the other hand, data with very high spectral resolution – hereafter referred to as imaging spectroscopy (IS) data, which is also known in the remote sensing community as hyperspectral (HS) data, has been successfully used in earlier studies to detect diverse mining environmental factors. Reflectance spectroscopy, both ground and image-based methods, has been successfully used to locate acid-generating minerals at mine sites (Kopačková et al., 2012b; Montero et al., 2005; Quental et al., 2013; Riaza et al., 2011a, 2011b; Richter et al., 2008, 2009; Swayze et al., 2000, 2006) and to determine heavy metal concentrations (Choe et al., 2008, 2009; Kemper and Sommer, 2002; Kopačková et al., 2011; Pandit et al., 2010). However, very few studies have been published on quantitative pH mapping in a mining environment (e.g., Ong and Cudahy, 2002; Zabcic et al., 2009). Particularly the extreme heterogeneity and the fact that the material is present in the form of mixtures rather than pure minerals (Montero et al., 2005; Riaza et al., 2011a) make quantitative pH mapping challenging. Therefore, the objectives of this paper are to:

- link the mineral, geochemical and spectral properties of the material at abandoned lignite mines and dumps;
- find spectral parameters reflecting the pH conditions which remain even if the minerals are present in the form of mixtures;
- employ a spectral mapping method that allows identification of the indicative minerals (based on the above considerations) even if present in mixtures and enable mapping of the pH spatial patterns using airborne multi-flight line hyperspectral data;
- build a pH model and validate the estimated pH using ground truth data.

2. Material and methods

2.1. Test site

The study was performed in the Sokolov basin in the western part of the Czech Republic (Fig. 1), in a region affected by long-term extensive lignite mining. The Sokolov basin, containing rocks of Oligocene to Miocene age, is 8–9 km wide and up to 36 km long, with a total area of about 200 km^2. The basin is limited by the Krušné Hory Fault (NNE-SSW trending) and is also characterized by a system of minor parallel faults, forming a significant tectonic zone of lithospheric extent (Ziegler, 1990). Another significant fault system of the Ohře Rift consists in the faults running in the NNW–SSE to NW–SE direction (Rajchl et al., 2009).

The basement of the Sokolov Basin is formed of Variscan and pre-Variscan metamorphic complexes of the Eger, Erzgebirge, Slavkov Forest, Thuring-Vogtland Crystalline Units and granitoids of the Karlovy Vary Pluton. The upper portions of these rocks are frequently weathered to kaolinitic residue. The basal late Eocene Staré-Sedlo-Formation is formed of well-sorted fluvial sandstones and conglomerates and is overlain by a volcano-sedimentary complex up to 350 m thick, which contains three lignite seams with a variable sulfur (S) content: the Josef seam (up to 20 m thick, 4.58% S), the Anežka seam (5–12 m thick, 1.57% S) and Antonín seam (20–30 m thick, reaching up to 62 m, 0.91% S) (Rojík, 2004; Murad and Rojík, 2005). The brown coal (lignite) belongs among coal seams enriched in As (Yudovich and Ketris, 2005) and other heavy metals, such as Cd, Ni, Cu, Zn, Pb (Bouska and Pesek, 1999).

Mining activities in this region have been documented since 1642. However large-scale underground and surface mining operations began only after 1870. In 2009 the Miocene Antonín seam was mined in the deeper part of the basin in two opencast pits, Družba and Jiří, but only the Jiri mine is still active at the present time. Long-term open cast mining required the removal of up to 180 m thick overburden (Cypris clays) which was stockpiled and replaced after the lignite was extracted. At the dumps, material consists mostly of Cypris clays, which can be characterized as well-laminated clays with different varieties of mineralogical composition: kaolinite, montmorillonite, illite with admixtures of Ca–Mg–Fe carbonates, sulphates, sulphides, analcite, Mg-micas and bitumen (Rojík, 2004). Due to the presence of S in the coal, the lignite mines both still active and abandoned, are largely affected by acid mine drainage (AMD) (Kopačková et al., 2011, 2012a).

2.2. Data

2.2.1. Aerial HS image datasets

The hyperspectral image data was acquired in 2009 (July 27) during the HyEUROPE 2009 flight campaign using the HyMap (HyVista Corp., Australia) airborne imaging spectrometer. The HyMap sensor records image data in 126 narrow spectral bands covering the entire spectral interval between 0.450 and 2.480 μm spectral range with Full Width Half Maximum (FWHM) of 15 nm and ground field of view of 4 m. The resulting ground pixel resolution of the image datasets was 5 m. In order to successfully pre-process the hyperspectral data, a supportive calibration and validation ground campaigns were organized simultaneously with the HyMap data acquisition in 2009 and 2010. At the selected homogenous targets the ground measurements were acquired by the ASD FieldSpec-3 spectroradiometer to properly calibrate as well as validate the image data and to enable: (i) atmospheric correction of the airborne hyperspectral images and (ii) retrieving at surface reflectance values for the further verification. The selected targets met the following conditions: (i) spatial homogeneity for a minimum area of 5×5 image pixels and (ii) natural or artificial nearly Lambertian ground surfaces. The hemispherical-conical reflectance factor (HCRF) (Schaepman-Strub et al., 2006) was measured for each reference target. Raw spectroradiometric data were transformed into the HCRF using the calibrated white spectralon panel. In addition, Microtops II Sunphotometer (Solar Light Comp., USA) measurements were taken approximately every 30 s during the HyMap data acquisition. Data acquired by the Sunphotometer were used for estimation of the actual atmospheric conditions (AOT – aerosol optical thickness; WV – water vapor content).

Nine individual HyMap stripes covered the entire area of the Sokolov lignite basin (Fig. 1). The orientation and geometry of the HyMap strips followed the SW–NE orientation of the lignite basin. This setting represented an optimal solution from the economic point of view; on the other hand, this setting (relative solar azimuth at the acquisition hour was about 73°) caused that the data suffered from strong cross-track illumination and bi-directional reflectance distribution function effects (Verrelst et al., 2008). Therefore, prior to atmospheric correction, the data had to be preprocessed to minimize these effects. The specific pre-processing focused on correcting the cross track illumination effect via (i) for each image separately, calculating the distribution of gases located in different spectral regions (O_2: 760 nm, H_2O: 930 and 1140 nm, CO_2: 2015 and 2060 nm) employing continuum removal (CR) and extraction of differences in gas absorption features across