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MAPPING SURFACE PH USING AIRBORNE HYPERSPECTRAL IMAGERY AT THE SOTIEL-MIGOLLAS MINE, SPAIN

Natalie Zabcic[1], Cindy Ong[2], Andreas Müller[3], and Benoit Rivard[1]

1. University of Alberta, Department of Earth and Atmospheric Sciences, Edmonton, Canada; nzabcic@ualberta.ca, benoit.rivard@ualberta.ca
2. CSIRO Exploration and Mining, Kensington, Australia; Cindy.Ong@csiro.au
3. DLR, German Remote Sensing Data Center, Wessling, Germany; Andreas.Mueller@dlr.de

ABSTRACT

Sotiel-Migollas mine is an abandoned lead, zinc and copper mine situated in Southwest Spain. The waste rocks, tailings and ores pose as an environmental problem when oxidation of these exposed materials cause acid drainage.

Hyperspectral technology has been used extensively to map and assess the impact of acid drainage (i, ii, iii, iv,). The aim of this study is to demonstrate quantitative multi-temporal monitoring capabilities using airborne hyperspectral data. Furthermore, a spectral prediction of surface pH was developed for the Brukunga Mine in South Australia (v, vi). The second aim of this study is to determine if that prediction is transferable to other mines such as the Sotiel Migollas in Spain.

The results from applying the pH prediction to multi-temporal data shows it is possible to obtain coherent pH maps which can be compared over time from properly corrected airborne hyperspectral data.

Further work is required to validate these maps

INTRODUCTION

Managing the environment is a primary concern for the mining industry. Effective and efficient tools for monitoring the environment are required to meet regulatory requirements and community expectation. This project serves to demonstrate remote sensing as a effective and accurate tool for monitor acid drainage (AD) conditions at a regional scale at mined lands. The results will help decision makers to spatially define the pollution risk at the mine and help focus remediation efforts as well as monitor the effectiveness of the remediation.

AD occurs when sulphidic material oxidises producing acid and releasing heavy metals. Effluents resulting from AD can seriously affect the surrounding environment. The oxidation reaction occurs naturally during the weathering of sulphidic material or can be enhanced by anthropogenic activities such as mining that exposes large amounts of metal sulphides to oxygen.

The, Secondary Fe-bearing minerals such as schwertmannite, ferrihydrite, jarosite, goethite, hematite and copiapite are produced with the oxidation of sulphidic materials (ii). These secondary minerals are the focus of this study because they form under different acidic conditions making it possible to infer and therefore monitoring the pH levels using remotely-sensed data.

pH prediction Model

The pH levels at which the Fe-bearing minerals precipitate are as follow: Jarosite: $pH < 3$; Schwertmannite: $pH = 2.8 - 4.5$; Mixtures of ferrihydrite and schwertmannite: $pH=4.5 - 6.5$; Ferrihydrite or a mixture of ferrihydrite and goethite: $pH > 6.5$ (vii,viii).

Authors from (v) and (vi) presented a spectral predictive model to generate predictions of surface pH from airborne hyperspectral imagery extending the application of hyperspectral sensing beyond mineral mapping of secondary minerals and demonstrated quantitative multi-annual monitoring capabilities.

The model was developed using partial least squares analysis PLS (ix), a statistical technique, applied to laboratory spectra and associated pH measurements of a comprehensive suite of samples covering the mine environment at a pyrite mine in South Australia. PLS analysis generates a set of final regression coefficients (FRC) for all the spectral bands. These FRCs, when applied to the spectral data, produce a prediction for the measurement of pH.

Objectives of this study

The objective of this study is to investigate if the predictive model developed at Brukunga Mine, Australia, is transferable to another mine site, that is, the Sotiel-Migollas Mine, Spain to provide quantitative multi temporal monitoring of AD and evaluate seasonal variations.

Study Site

This study focuses on the Sotiel-Migollas mine situated in Southwest Spain. Sotiel-Migollas is an abandoned underground mine complex within the volcanic siliceous complex of the Upper Devonian-Lower Visean located in the Iberian Pyrite Belt (IPB) (x, xi,xii), (Figure 1). This mine operated from 1984 to 2002. The main commodities were lead, zinc and copper but the operations also included sulphide ore extraction for the production of sulphuric acid (xiii). The main source of contamination is the mine waste, releasing high concentrations of heavy metals and acidic waters into the Odiel River where pH values of 2.2 - 3.6 are measured (xiv, xv). The Odiel River flows directly into the Gulf of Cadiz via the Huelva estuary zone. The estuary contains acid waters and sediments with high Fe_2O_3, Cu, Zn, Pb, and Ba concentrations from the Odiel and Tinto rivers (xvi). These conditions result in it being rated one of the most polluted water systems in Western Europe (viii).

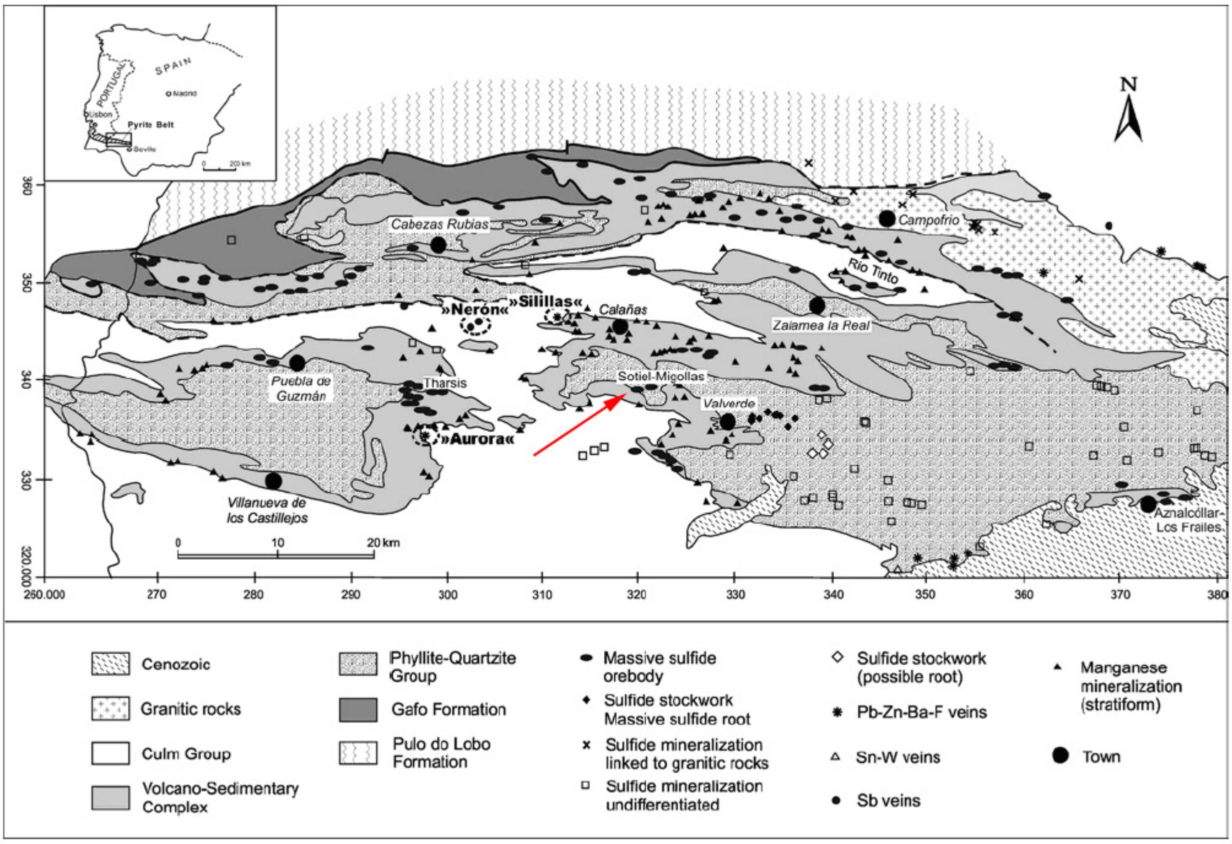

Figure 1: Location of deposits in the Spanish part of the Iberian Pyrite Belt (modified after xii). The arrow marks the study site.

METHODS

Airborne acquisition

Airborne hyperspectral data (HyMap) was acquired over the Sotiel-Migollas Mine on May 6, 1999, May 19, 2004 and August 14, 2004. The HyMap data were acquired during the flight campaigns carried out by the German Aerospace Center (DLR). The 128 channel HyMap data (450 - 2500 nm) were acquired at 5 m for the 1999 and 4 m pixel resolution for the 2004 datasets.

Field spectral measurements

Field spectral validation and calibration data were acquired concurrent with the airborne acquisitions in 2004. These field spectra were collected using the Analytical Spectral Device (ASD) Fieldspec FR Spectrometer, covering the 350-2500 nm wavelength range.

Spectral measurements were collected at four invariant targets consisting of a soccer playing field, a basketball court, a concreted playing field at a primary school and a car park.

Samples representative of the different minerals covering the mine environment were also collected for validation purposes.

Pre-processing

The pre-processing of the data involved atmospheric correction using ATCOR, a program based on radiative transfer modelling of MODTRAN. This is followed by empirical line correction using the field-acquired spectral data acquired at invariant targets to retrieve accurate surface reflectance measurements.

RESULTS

The predictive model developed for Brukunga was applied to the corrected airborne data acquired in May 1999, May 2004 and August 2004. The maps generated are presented on figure 2.

The multi-temporal dataset allows for comparisons between dates. Qualitative comparisons show that in 1999, the tailings around the processing plant appear to have increase in size. The data indicates that pH levels have increased in the last 5 years, possibly related to remediation efforts to neutralise the tailings. The seasonal variations captured between May and August 2004 indicates a general decrease in pH in zones A, B, and C and an increase in zone E. The increase in zone E may be a result of a drier and well drained surface associated with higher relief. Zones A, B, and C may have been affected by rain between May and August. Efflorescent salts developed during dry periods could have dissolved with rain to form acid. Below describes the multi-temporal variation at specific areas.

- **Zone A:** The tailings ponds appear to have increased by approximately 1.2 km^2 since 1999. Between May and August 2004 pH levels are generally constant (pH = 3-5) with a few additional patches of pH = 2-3 in August 2004.
- **Zone B:** This area appears to be very acidic in 1999 (pH = 2-5) compared to neutral-basic levels in 2004. There appears to be little seasonal variation between May 2004 and August 2004 where the pH has decreased from pH = 7-13 to 7-9 respectively.
- **Zone C:** The outer part of this pond tailing shows an increase in pH levels from 1999 to 2004 (from pH = 4-6 to 7-10). In May and August 2004 the levels remain constant with a few patches of lower pH.
- **Zone D:** The Odiel River bank is mapped as more acidic conditions in 1999 (pH = 2-4). In May and August 2004, the pH levels are at 3-5 and remain constant between these two months.
- **Zone E:** The area is mapped at a pH value of 3-7 in 1999:. In May 2004, the levels are neutral (pH = 6-9) with two patches of (pH = 4-5). In August 2004, the conditions are neutral to basic (pH = 6-11).

The pH maps obtained for the Sotiel-Migollas mine using the model created at Brukunga present coherent results, that is, the pH values are within the expected range of AD conditions (iii, iv) and the low pH materials are mapping in areas such as the tailings dam and river banks where those level are expected. It is still unknown whether the pH values obtain from the predictive model are accurate. Validation of these maps is required to determine the transferability of the models. This will be the next stage of the work.

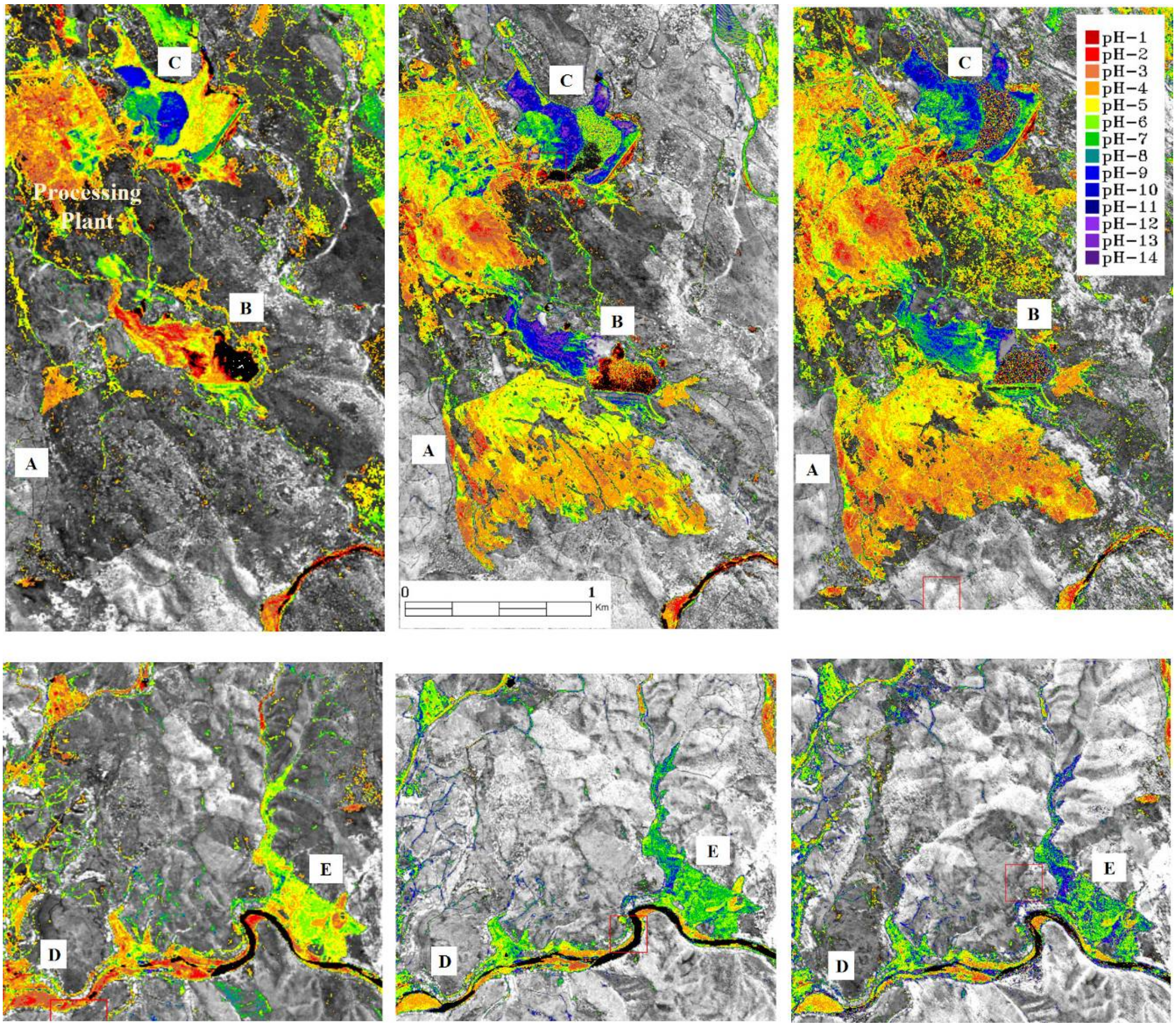

Figure 2: Multi-temporal series of predicted pH maps over the Sotiel-Migollas Mine. Zone A: Tailings near the processing plant; B and C: Pond tailings; D: Odiel river bank; E: Main tailing site.

SUMMARY AND FURTHER WORK

The outcome of this study is the characterization of changing surface pH conditions over seasonal and annual time for the Sotiel-Migollas mine complex. Quantitative measurements (e.g. pH) are understood to be the key data to evaluate mining environments. Traditional quantification of mine waste requires intensive collection of mineral samples and subsequent laboratory analysis. This study illustrates a monitoring capability with a fast, cost-effective, non-destructive and non-hazardous method to extract quantitative pH information. Further work will include validating the predicted pH maps with pH measurements collected concurrently. A site-specific pH model for Sotiel-Migollas Mine may be required.

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REFERENCES

i Swayze, G.A., Clark, R.N., Pearson, R.M., Livo, E. K., 1996. Mapping Acid-Generating Minerals at the California Gulch Superfund Site in Leadville, Colorado using Imaging Spectroscopy. In: Summaries of the 6th Annual JPL Airborne Earth Science Workshop March 4-8, 1996. Internet: http://speclab.cr.usgs.gov/PAPERS.Leadville95/leadville1.html.

ii Chabrillat, S., Goetz, A.F.H., Krosley, L., Olsen, H.W., 2002. Use of hyperspectral images in the identification and mapping of expansive clay soils and the role of spatial resolution. Remote Sensing of Environment, 82: 431-445.

iii Dalton, J.B., King, T.V.V., Bove, D.J., Kokaly, R.F., Clark, R.N., Vance, J.S., Swayze, G.A., 2000. Distribution of Acid-Generating and Acid-Buffering Minerals in the Animas River Watershed as Determined by AVIRIS Spectroscopy. In: Proceedings of the ICARD 2000 Meeting, May 21-24, 2000, Denver Colorado.

iv Kemper, T., Sommer, S., 2003. Mapping and monitoring of residual heavy metal contamination and acidification risk after the Aznalcollar mining accident (Andalusia, Spain) using field and airborne hyperspectral data. In: 3rd EARSEL Workshop on Imaging Spectroscopy, edited by M Habermeyer, A Müller & S Holzwarth (EARSeL, Paris), 333-343.

v Ong, C., Cudahy, T.J., 2002. Deriving Quantitative Monitoring Data Related to Acid Drainage using Multi-Temporal Hyperspectral Data. In: 2nd EARSEL Workshop on Imaging Spectroscopy, (EARSeL, Paris).

vi Ong, C., Cudahy, T.J., Swayze, G., 2003. Predicting Acid Drainage Related Physicochemical Measurements Using Hyperspectral Data. In: 3rd EARSEL Workshop on Imaging Spectroscopy, edited by M Habermeyer, A Müller & S Holzwarth (EARSeL, Paris), 363-373.

vii Jönsson, Jörgen (2003). Phase transformation and surface chemistry of secondary iron minerals formed from acid mine drainage. Doctoral Thesis(2005-02-02). http://urn.kb.se/resolve?urn=urn:nbn:se:umu:diva-156

viii Bigham, J.M., Schwertmann, U., Pfab, G., 1996. Influence of pH on mineral speciation in a bioreactor simulating acid mine drainage. Applied Geochemistry, 11: 845-849.

ix Haaland, D.M. and Thomas, E.V. (1988). Partial Least Squares. Analytical Chemistry, 60: 1193-1200.

x Barriga, F.J.A.S., 1990. Metallogenesis in the Iberian Pyrite Belt. Pre-Mesozoic Geology of Iberia, Chapter 5, (R. D. Dallmeyer and E. Martinez Garcia Editions)369-379.

xi Carvalho, D., Barriga, F.J.A.S., Munha, J., 1999. Bimodal siliciclastic systems – the case of the Iberain Pyrite Belt. In: Barrie C.T. and Hannington M. D., eds., Volcanic-Associated Massive Sulfide Deposits: Processes and Examples in Modern and Ancient Settings, Reviews in Economic Geology, SEG, 8: 375-408.

xii Leistel, J. M., Marcoux, E., Thiéblemont, D., Quesada, C. , Sánchez, A., Almodóvar, G. R., Pascual, E. , Sáez, R., 1997. The volcanic-hosted massive sulphide deposits of the Iberian Pyrite Belt. Mineralium Deposita, 33 (1 – 2): 2-30.

xiii Morales J.R., 1999. Present Status of IPB Activity: A Case of Re-emergence of Mining Activity in Europe?. Mining Development Strategies with a Focus on the Case of the Iberian Pyrite Belt. Technical Journey 25th September 1998 Lisbon, Portugal. http://www.igm.pt/edicoes_online/diversos/mining_develop/capitulo1.htm.

xiv Braungardt, C.B., Achterber, E.P., Elbaz-Poulichet, F., 2003. Metal geochemistry in a mine-polluted estuarine system in Spain. Applied Geochemistry, 18: 1757-1771.

xv Borrego, J., Morales, J.A., de la Torre, M.L., Grande, J.A., 2002. Geochemical characteristics of heavy metal pollution in surface sediments of the Tinto and Odiel river estuary (southwestern Spain). Environmental Geology, 41: 785-796.

xvi Braungardt, C., Achterberg, E.P., Nimmo, M., 1998. On-line voltammetric monitoring of dissolved Cu and Ni in the Gulf of Cadiz, south-west Spain. Analytica chimica acta, 377: 205-215.