Integrating hyperspectral analysis and mineral chemistry for geoenvironmental prediction

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Abstract

Hyperspectral drill core scanning technology (e.g., CoreScan®), which uses visual near-infrared (VNIR), shortwave infrared (SWIR), and longwave infrared (LWIR) data, is being increasingly used for geological domaining of ore deposits. Advantageously, this technology can identify carbonate-group minerals that can effectively neutralise many mine wastes. The chemistry of neutralising minerals in drill core can also be routinely analysed by multiple techniques (e.g., portable X-ray fluorescence (pXRF), laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS),) but hasn't been integrated with hyperspectral data for deposit-scale geoenvironmental characterisation.

In this study we integrate hyperspectral mineral data with a newly developed LA-ICP-MS line-scan method to characterise major and trace element chemistry of neutralising minerals in drill core. We demonstrate how this data can enable effective geoenvironmental domaining of ore deposits with examples from a porphyry Au-Cu deposit in Australia. We validate Corescan® data using X-ray diffractometry (XRD) and a series of acid-base accounting tests to define geological domains with high and low acid neutralising capacity (ANC). The distribution and abundance of trace elements are defined in these domains using by LA-ICP-MS. A new geoenvironmental domaining index (GDI) is developed using Corescan® data, which can assist with deposit-wide characterisation.

The rapid and cost-effectiveness of hyperspectral core scanning and LA-ICP-MS techniques makes them critical emerging technologies for routine geoenvironmental risk domaining using drill core. Here we emphasize that integrating these techniques potentially enables best practice ARD management at the beginning of the life-of-mine cycle by allowing early forecasting of the geoenvironmental properties of future wastes.

Keywords: Hyperspectral, mineralogy, geoenvironmental domaining, prediction, LA-ICP-MS

Introduction

Waste produced by the Mining Industry is one of the largest industrial waste streams on the planet with an estimated 4–15 Gt of broken waste rock and tailings produced annually (Lottermoser, 2010; Haas et al., 2015; Lèbre et al., 2017). The increased potential for acid and metalliferous drainage (AMD) from mining activities and mine waste poses a serious threat to the environment (e.g., Gurung et al., 2017; Anderson and Butler, 2017). Although Industry-wide geoenvironmental predictive codes (e.g., AMIRA, 2002; MEND 2009 guidelines; ASTM methods (e.g., D5744-13e1, D6234-13)) can discriminate between acid-forming and acid-neutralising mine wastes (Ashley et al., 2004), they are fraught with limitations and can easily be misused (Dold, 2016). Sampling protocols may also inadequately assess the acid-forming or acid-neutralising characteristics of an ore deposit. For example, Price (2009) suggests at least 3–5 representative samples should be tested for each key lithology or alteration type at the exploration stage of the mine life cycle. Following this suggestion, a newly discovered ore deposit with 4 alteration types would require only 12–20 samples for geoenvironmental testing, which would be assumed to be representative of the thousands of tonnes of waste rock produced during the life of the mine. Successful geoenvironmental characterisation early in the life of mine can be more cost effective than rehabilitation upon mine closure.

Modern analytical techniques such as hyper-spectral core scanning, LA-ICP-MS, portable XRF, present an opportunity to optimise the use of waste material for mine rehabilitation. These techniques can identify neutral or acid-neutralising waste material during the early life of the mine, which can assist in minimising and treating AMD, avoiding the need to import costly neutralising materials. This study uses drill core from a porphyry Au-Cu mine to develop and test new hyperspectral protocols to enhance deposit-scale geoenvironmental domaining. The goal is to integrate key mineralogy and mineral chemistry data for early forecasting of geoenvironmental properties of waste materials, creating the opportunity to transform how waste materials are characterised and managed over the life of a mine.

Methods

Hyperspectral analysis was conducted using a Corescan® HCI-3 system operating across the VNIR and SWIR bands from 450 nm-2500 nm collecting continuous images of rough sawn half core (n=100) representing various alteration styles from 7 drill holes of a porphyry deposit. Specifics of the Corescan® instrument used were as follows: spectral resolution ≈4 nm; photography, 50 μm pixels; spectral imagery, 500 μm pixels; and profiler image, 200 μm. High quality optics focused spectral measurements to a 0.5 mm point on the core resulting in ≈ 150,000 spectra per meter of scanned core. A spectrally calibrated RGB camera provided a high-resolution visual record of the core at 60 μm per pixel. Core surface features, texture, and shape was captured using a 3D laser profiler with a surface profile resolution of 20 μm. The data was used in geoenvironmental domaining index (GDI) calculations following Jackson et al. (2017), which considers the carbonate, and/or silicate abundance at each measured point and multiplies this by relative reactivity and theoretical neutralising capacity values. High GDI values (>400) represent areas dominated by carbonate, which have the largest ANC potential. Low values (<100) represent areas with < 10% primary neutralisers, with lower ANC potential.

To validate Corescan® results, the bulk mineralogy of the same samples (n=100) were analysed using a benchtop Bruker D2 Phaser XRD instrument with a Co X-ray tube, at the University of Tasmania (UTas). Samples were crushed and milled, following by micronizing of 2 g of sample with a Retsch micronizing mill with zirconium oxide grinding elements for 10 minutes using ethanol and oven-dried overnight at 40°C. Individual XRD analyses were performed using a step size of 0.02 $°2\theta$ with a dwell time of 0.4 seconds/step at an operating voltage of 30 kV and 10mA. Minerals were identified using the Bruker DIFFRAC. EVA software package with the PDF-2 (2012 release) powder diffraction file mineral database. Mineral abundances were semi-quantified by Rietveld refinement using TOPAS (Version 4.2) pattern analysis software.

The current alkalinity of each sample was assessed using ASTM D4972-13 (2013) paste pH method at UTas following Noble et al. (2015). Measurements of total sulfur (%) for the calculation of maximum potential acidity (MPA) and total carbon (%) were performed using a Thermo Finnigan EA 1112 Series Flash Elemental Analyser. Multi-addition net acid generation (mNAG) pH testing and ANC testing was conducted following the AMIRA P387A AMD Test Handbook methods (Smart et al., 2002) with NAPP values calculated accordingly.

Mineral chemistry was measured on unpolished drill core (n=7) using LA-ICP-MS following the method piloted by Meffre et al. (2017). Measurements were conducted on an Agilent 7900 quadrupole ICP-MS coupled to a Resonetics RESOlution ablation cell and a 193 nm Coherent COMPex Pro ArF excimer laser. A total of 45 elements were analysed simultaneously using a 50 μm spot size pulsing at 20 Hz and moving along the core at 100-150 μms^{-1}. Data was processed using in-house software that corrects for the different ablation rates of various minerals and mineral mixtures (Meffre et al., 2017).

To identify if data produced by µXRF is useful in the context of producing textural maps showing mineral chemistry (to compliment LA-ICP-MS), analyses on select samples (n=7) were performed at the CSIRO Advanced Characterisation Facility, Perth. Samples (≈11 x 5 x 1 cm) were mapped using a Bruker M4 Tornado using a Rh X-ray source (50 kV, 600 µA) under vacuum using a 25 µm spot size, a step size of 40 µm and dwell time of 5s. A flat surface was the only sample preparation requirement. Qualitative element abundance maps with an atomic number greater than 12 (i.e., heavier than Mg) were output.

Results

Mineralogy of the analysed drill holes is dominated by quartz, feldspar, chlorite, and epidote. Calcite is the dominant carbonate (max 50.9 wt. %). Sulfides include pyrite (max 31.6 wt. %) and chalcopyrite (max 2.1 wt. %). Calcite abundance determined from Corescan® was compared against XRD and total carbon values (C_{TOTAL} % x 8.33; Herrmann and Berry, 2002) to validate these results. A comparison of calcite abundance using these three techniques is presented in Fig 1 and shows high R^2 values (range: 0.57-0.8) ($Calcite_{Corescan}$ average: 2.8 wt. %, max: 34.4 wt. %; $Calcite_{XRD}$ average: 8.9 wt. %, max: 50.9 wt. %; $Calcite_{calculated}$ average: 7.1 wt. %, max: 48 wt. %). Comparisons imply that Corescan® data is sufficiently accurate for the purpose of domaining.

Using Corescan® data, GDI values were calculated for discrete samples, up to 30 cm length, from one drill hole (Fig. 2) with values shown alongside continuous alteration and static data (e.g., S %, mNAG, ANC, MPA). High GDI values (classified as extremely low risk; Jackson et al., 2017) strongly correlate with static data (e.g., 150 m: GDI 344; paste pH 8.3; mNAG pH 9.3; S_{TOTAL} 0.3%; MPA 10 kgH_2SO_4/t; ANC 1132 kg H_2SO_4/t). These results show that GDI values are able to independently define neutralising zones when compared to static data.

To demonstrate how hyperspectral and LA-ICP-MS data can be used for geoenvironmental domaining, we show the classified mineralogy, static testing, µXRF, and LA-ICP-MS data for one drill core sample

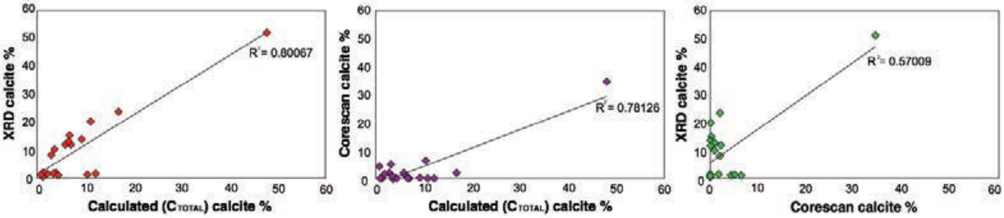

Figure 1 *Comparison of calcite identification from XRD, Corescan® and calculated from total carbon values.*

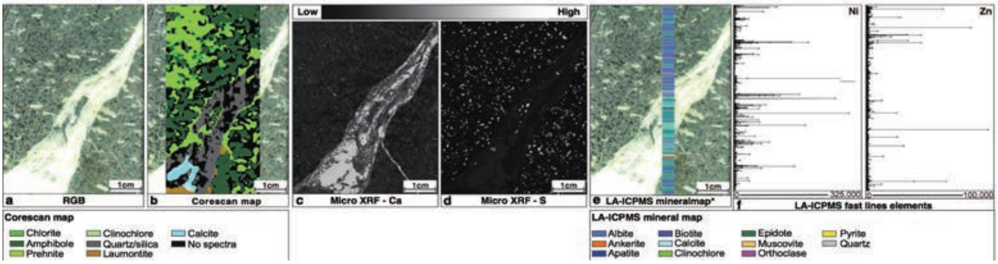

Figure 2 *Drill core slab displaying mineralogy and trace element chemistry collected using different techniques; Corescan® classified mineral map, micro X-ray fluorescence (µXRF), mineral liberation analysis (MLA), laser ablation inductively coupled plasma mass spectroscopy (LA-ICP-MS) collected as fast line scans elemental data and derived mineralogy. * LA-ICP-MS line not true line width to allow for visual representation.*

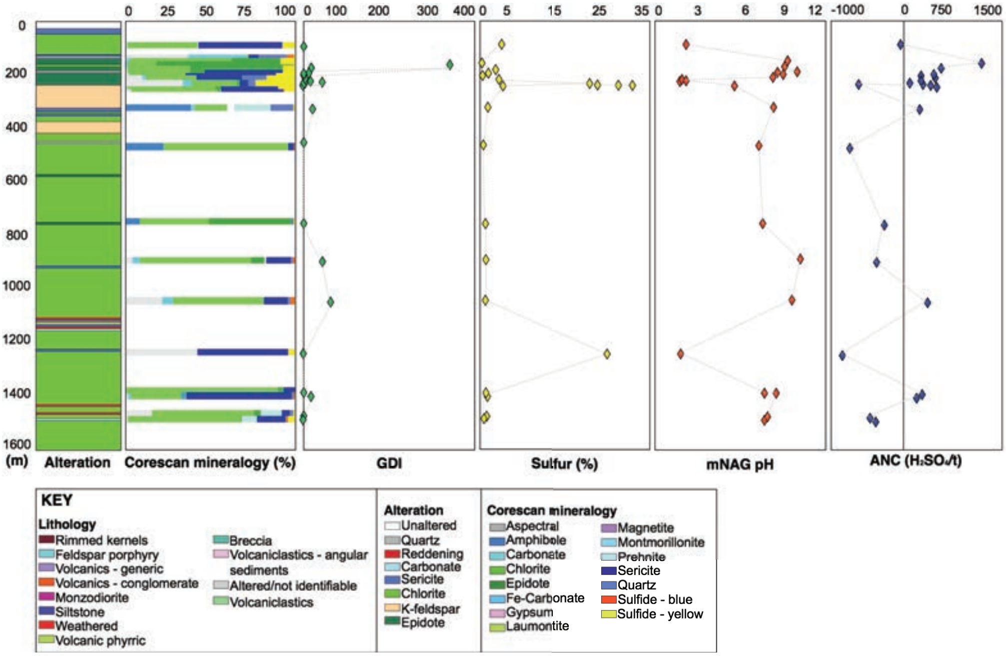

Figure 3 Down-hole log displaying lithology and alteration against Corescan® classified mineral map, geoenvironmental domaining index (GDI), sulfur %, paste pH, multi addition net acid generation (NAG) pH, acid neutralising capacity (ANC) and maximum potential acidity (MPA) value.

(Fig 2). Static testing confirmed its high ANC (227 kgH_2SO_4/t) and negative NAPP (-185.6 kgH_2SO_4/t) with a calculated GDI of 21.57 (i.e., low risk). Fig 3d shows the µXRF S map and highlights sulfide group minerals pyrite and chalcopyrite present in the sample's groundmass. Although the µXRF images are not quantitative, the high resolution of this technique shows the distribution of sulfur, which can be used as a proxy for sulfides. As sulfides do not have a spectral signature in the IR region this can be used effectively with Corescan® data to resolve mineralogy of aspectral data.

Fig 3e shows calculated mineralogy based on 1,769 data points from a single LA-ICP-MS line across the drill core surface. This data correlates strongly to classified mineralogy (active in SWIR region) output by Corescan® (Fig. 2b). Examples of trace element distribution (Fig. 3f) along the LA-ICP-MS line indicate that calcite contains Zn (max: 1,235 ppm, average: 259 ppm) and Ni (max: 12,397 ppm; average: 269.1 ppm). Both Ni and Zn values are above ANZECC (2000) 90% species protection freshwater trigger values (0.013 ppm and 0.008 ppm respectively). Other trace elements above the ANZECC (2000) 90% species protection trigger values for freshwater include mean values Al: 8,139 ppm, As: 11.9 ppm, Cu: 337 ppm and Pb: 145 ppm.

Discussion

Mineralogy and texture are significant factors that influence contaminant release from waste rock materials but are not assessed by static tests. Thus, critical information regarding the onset and longevity of AMD can be misunderstood. Parbhakar-Fox and Lottermoser (2017) initially demonstrated how Hylogger™ hyperpspectral data could be used to rapidly perform AMD risk assessment for drill core materials. Advantageously, Corescan® records high-resolution RGB images and textural data along with mineralogy. As Corescan® measures in the SWIR region only, mineralogical identification could be improved with hardware modifications to allow for spectral analysis in the LWIR region. This would enable for mineral speciation (e.g., carbonate group– calcite, dolomite, ankerite, siderite) therefore improving GDI calculations.

Some specific advantages of the GDI include: (1) Its ability to domain large volumes of drill core faster than visual logging; (2) Reduction of expenditure for mineralogical testing (i.e., Corescan® + C_{TOTAL} in place of XRD); (3) Reduction of cost for static testing (i.e., select representative samples identified from Corescan® for validation); (4) The preservation of the textural context of neutralising minerals and the ability to characterise these textures at high spatial resolution allows for liberation forecasting (i.e., course grained calcite would dissolve slower over time compared to disseminated calcite and therefore have a longer neutralising effect).

Characterising trace element chemistry of waste rock is an essential pre-requisite to assessing whether material is an effective neutraliser that will not compromise the downstream environment (Lottermoser, 2010). The LA-ICP-MS fast line method offers a new opportunity to quantify trace element chemistry in drill core or waste rock. This method delivers both classified mineralogy and mineral chemistry. Limited sample preparation requirements, cost efficiency, speed, low detection limits, and the ability to simultaneously analyse a large suite of elements is far advantageous over other methods (e.g., chemical leach sequential extractions; Fig. 3f). The limitations of LA-ICP-MS fast line scanning such as differing mineral ablation rates and mixing of spectra can mostly be overcome by post-analysis data processing (Meffre et al., 2017). Fig 2 demonstrates the potential of combining LA-ICP-MS line-scanning results with high spatial resolution µXRF maps to effectively characterise the distribution of minerals hosting deleterious trace elements in texturally complex samples. This new method is limited to single line data, future development potentials include mapping functions to produce outputs similar to µXRF but with advantages of both quantified element chemistry, mineralogy, and low detection limits.

Conclusions

Integrating quantitative mineralogy (Corescan®) with trace element chemistry (LA-ICP-MS) from drill core produces unprecedented recognition of low trace element content acid neutralising waste rock within an ore deposit. In this study Corescan® data was used to calculate GDI values drill core to identify samples with effective neutralising capacity. Trace element analyses using LA-ICP-MS line scan method identified the calcite as Zn and Ni rich, which should be considered when planning waste pile design. Modifications to Corescan® processing techniques are being investigated to resolve aspectral fractions (e.g., Cracknell et al., 2017). Improved aspectral identification will produce an enhanced sulfide recognition workflow. Amendments will produce an updated and comprehensive index more comparable to NAPP.

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