INTRINSIC NEUTRALISATION POTENTIAL FROM AUTOMATED DRILLCORE LOGGING FOR IMPROVED GEOENVIRONMENTAL DOMAINING

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ABSTRACT

Hyperspectral analysis integrating near-infrared (NIR), shortwave infrared (SWIR) and longwave infrared (LWIR) spectrometry can accurately identify carbonate, silicate and serpentine-group minerals. Significantly these mineral-groups offer short and long term neutralising capacity respectively in a range of mine waste environments. Routine hyperspectral mineral analysis is increasingly used for geometallurgical and geological domaining of ore deposits; however the mineralogical information obtained is rarely used for deposit-scale geoenvironmental characterisation. Evaluating the location, volume, and chemistry of neutralising gangue materials early in the mine planning process will permit prudent economic forecasting with regards to mine closure and beyond. By accurately identifying short- and long-term neutralising minerals in low (or below) grade material, their use within rock and tailings storage facilities can help to alleviate the need to acquire costly neutralising materials particularly at the time of mine closure.

This study focusses on using data generated by hyperspectral mineralogy platforms to develop geoenvironmental domaining algorithms. Seven drill holes from a porphyry Au-Cu deposit were analysed, with hyperspectral results validated against established geoenvironmental characterisation tests (including acid base accounting and X-ray diffractometry). These data show that neutralising characteristics of differing alteration types can be predicted accurately from hyperspectral data. Furthermore, when used in conjunction with NAG pH, these data could be used to precisely identify neutralizing and acid forming zones.

1.0   INTRODUCTION

Mining impacts on the environment can occur at any point during the life-of-mine (LOM) with many examples published in the scientific literature (e.g., Hyndman, 2001, Harris et al., 2003, Edraki et al., 2005, Parbhakar-Fox et al., 2014, Candeias et al., 2014, Staebe, 2015 and Myers, 2016). While sulfide oxidation and acid and metalliferous drainage (AMD) is significant, other environmental impacts of mining include: vegetation clearance for the construction of access roads, infrastructure (e.g., processing, milling, survey lines, drill sites, and exploration tracks); hydrological disturbance; creation of waste repositories and landforms (e.g., tailings dams and waste piles); surface subsidence, excessive water use, dust generation, and release of solid, liquid, or gaseous contaminants into surrounding ecosystems (e.g., Castilla

1993; Harries 1997; Davis et al., 2000; Harris et al., 2003; Edraki et al., 2005; Candeias et al., 2014; Schoenberger, 2016 and Venkateswarlu et al., 2016). Failure to predict and manage mine waste appropriately from the beginning of operation, such as at the Mt Lyell mine, (Waggitt and Jones, 1996) and Rio Tinto (Hudson-Edwards et al., 1999), highlights the extensive timeline of continual metal leaching and AMD resulting in long-term ecosystem degradation.

Australia alone has more than 60,000 abandoned mines (ABC, 2017), some of which represent a significant threat from contamination; others may pose safety risks; and still others may be losing their value as cultural heritage (Unger et al., 2011). Estimated rehabilitation costs for mining legacy sites are over AUD \$1 billion in liabilities (Pepper et al., 2014), which is considered much greater than the cost of managing potentially acid forming wastes during mine operation. Mudd (2008) stated that lower grade ore deposits are being exploited for a large-range of commodities (e.g., Ag, Au, Cu, Sn); consequently the mining industry is producing significant volumes of mineral waste, approximately 4 gigatonnes/year (Haas et al., 2015). Globally, mineralized waste is one of the largest industrial waste streams (Lèbre et al., 2017).

The mining industry needs protocols in place to effectively minimise environmental footprints and work towards benign mine closure. An understanding of the long-term release of contaminants requires a solid knowledge of the factors that control discharge. However, the most significant factor influencing contaminant release is the mineralogy (and textural arrangement of these minerals) of the resource host rocks and therefore is critical to define for adequate geoenvironmental prediction. Robust upfront mineralogical characterisation could not only prove advantageous in the long-term for environmental management but also could result in identification of useful secondary remediation materials which would otherwise end up in the waste rock piles or tailings dams. Therefore, the challenge is to develop predictive AMD protocols that can be implemented in early LOM stages, (i.e., pre-feasibility/feasibility) to effectively characterise waste material in order to minimise potential AMD liabilities. This would allow for a detailed understanding of the AMD and metal leaching characteristics of a deposit to be established prior to mine operation. In this study, drill core from an operating porphyry Au-Cu mine was used to develop and test this new methodology.

2.0 MATERIALS AND METHODS

2.1 Mineralogical Characterisation

2.1.1 Hyperspectral analysis

Split drillcore were scanned using the Corescan® HCl- 3 system. The scanning measurements operate across the VNIR and SWIR bands from 450 nm – 2500 nm at a spectral resolution of ~4 nm (Figure 1). The Corescan® system produces full, continuous images along-core, with operating ranges as follows: photography, 50 μm; spectral imagery, 500 μm; and profiler image, 200 μm. High quality optics focus the spectral measurement to a 0.5 mm point on the core, maximising signal (average 2000:1 across the measured spectrum) and minimising spectral mixing therefore providing a near-pure spectral signature at each point on the core. This results in ~ 150,000 spectra per meter of scanned core. In addition, a spectrally calibrated RGB camera provides a high-resolution visual record of the core at 60 μm-pixel size. Measurement of core surface features, texture and shape is captured using a 3D laser profiler with a surface profile resolution of 20 μm.

The Corescan® hyperspectral imaging data were processed in-house. Reflectance spectral signatures were compared to an amalgamated reference spectral library. Identification and classification of mineral signatures were performed with proprietary Corescan® software based on a linear regression technique that isolates the position and overall architecture of spectral absorption minima and maxima that uniquely identify specific minerals (Martini et al., 2014). Classified mineral maps for the core are used to compute relative downhole mineralogy counts (exported as .csv files). The final 'product' identified 17 minerals and 3 additional mineral mixtures, and these were used to create mineral distribution, composition and classification maps. Aspectral is reported for minerals that do not reflect in the VNIR and SWIR spectrum.

Figure 1. Portable Corescan® container and instrument.

2.1.1.1   Hyperspectral sample selection

Corescan® offers visual classified mineral maps of continuous drillcore through an interactive viewing platform called Coreshed. Classified mineral maps of complete drillholes (*n=5*) were used to domain and guide sample selection (Figure 2). Figure 2 demonstrates how drillholes were broken up into mineralogical domains, drill tray numbers were selected from these domains, and a sample was chosen at random from the selected tray to best represent that domain.
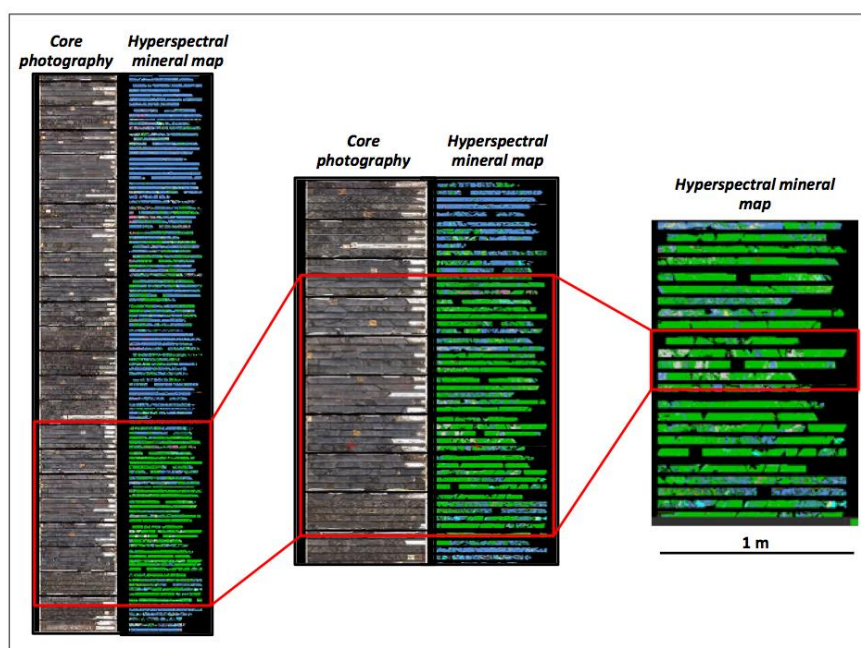
Figure 2. Example of Coreshed viewing platform used for mineralogical domain driven sampling. Red boxes indicate sampling guides and propagation to sample selection.

2.1.1.2   Hyperspectral geoenvironmental domaining

Corescan® offers visual qualitative mineralogical assessments through Coreshed. However, to gain semi-quantitative mineralogy, mineral counts were extracted and relative downhole mineralogy was used to calculate relative abundance. Individual mineral relative abundance was converted to percentage (*Equation 1*).

(min 1 counts/(min 1 counts + min 2 counts + min 3 counts)…)   *(Eq. 1)*

This can then be used to compare mineralogy on a sample by sample basis. This mineral percentage was multiplied by recognised mineral standard values obtained under experimental conditions. Jambor et al. (2007) and Parbhakar-Fox and Lottermoser (2014) measured neutralising potential (NP) for pure mineral specimens, and Sverdrup (1990) measured relative reactivity (RR) of pure mineral specimens (Table 1). These standards were used in the algorithm to allow forecasting of acid neutralising behavior (*Equation 2*), which we have termed Geoenvironmental Domaining Index (GDI).

(Min1%*((NP or AP)*RR)*1000)+(Min2%*((NP or AP)*RR)*1000)+(Min3%*((NP or AP)*RR)*1000)…   *(Eq. 2)*

To simplify this algorithm, we used a scaled standard number for each mineral which accounts for both NP and RR and have termed it the Geoenvironmental Domaining Index Standard (GDIS). Equation 2 can be shortened (*Equation 3* and Table 1). Table 2 shows mock examples of how the GDI can change based on mineralogy.

(Min1%*(GDIS))+(Min2%*(GDIS))+(Min3%*(GDIS))…   *(Eq.3*

Table 1.   Mineral neutralising potential values, relative reactivity values and corresponding GDIS values used for this study. * Indicates mineral mixtures where two separate spectra are unable to be separated due to small grain size and intergrowths.

Mineral	Neutralising Potential (kg CaCO₃/t) *Jambor et al. (2007); Parbhakar-Fox and Lottermoser (2014)*	Relative Reactivity *Sverdrup (1990)*	Geoenvironmental Domaining Index Standard (GDIS)
Amphibole	0.003	0.02	0.06
Aspectral	0	0	0
Biotite		0.02	0
Carbonate	1	1	1
Chlorite	0.006	0.02	0.12
Epidote	0.001	0.02	0.02
Gypsum	0.008	1	8
Laumontite	0.002	0.004	0.008
Magnetite	0	0.02	0
Montmorillonite	0.001	0.02	0.02
Phlogopite	0.008	0.02	0.16
Prehnite	0.006	0.02	0.12
Saponite	0.001	0.02	0.02
Sericite	0.001	0.01	0.01
Silica/quartz*	0	0.004	0
Tourmaline	0	0.02	0

Table 2. Mock examples of differing mineral combinations and corresponding GDI values.

Example	Mineral 1	%	Mineral 2	%	Mineral 3	%	GDI value
A	Carbonate	80	Quartz	20	-	-	**80**
B	Carbonate	50	Chlorite	30	Quartz	20	**53.6**
C	Carbonate	20	Chlorite	60	Quartz	20	**27.2**
D	Chlorite	80	Quartz	20	-	-	**9.6**

Table 3. First pass GDI risk classification

GDI value	GDI risk grade	Description of AMD risk classes
0 to 100	Low/potential risk	Dominated by silica/quartz, sericite, chlorite. Few sulfides present, primary neutralisers < 10%.
100 to 400	Low risk	Carbonate present as first mineral: 40 to 10%.
400 to 1,000	Very low risk/ ANC potential	Carbonate dominate as first mineral > 40%. Long term net-neutralising capacity likely.

2.1.2   XRD

To determine the bulk mineralogy, samples were analysed using a benchtop Bruker D2 Phaser XRD instrument at the University of Tasmania (with a Co X-ray tube). All drillcore samples were crushed, milled and micronised. Analysis was performed for 1 hour 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.

2.2   Static Testing

The current acidity was assessed using the ASTM D4972-13 (2013) paste pH method following recommendations given in Noble et al. (2015). In addition, measurement of total sulfur (wt. %) for the calculation of maximum potential acidity (MPA) was performed using an Eltra C-S 2000 *(n=30)* with AR4015 and AR007 standards and a Thermo Finnigan EA 1112 Series Flash Elemental Analyser *(n=70)*. Sample duplicates and blanks were incorporated to enable data processing, when both instruments were used. Multi-addition net acid generation (NAG) pH testing was conducted following the method outlined in Smart et al. (2002). Acid neutralising capacity testing (ANC) was conducted following the AMIRA P387A AMD Test Handbook method (Smart et al., 2002).

3.0   RESULTS

One example from the skarn alteration type of the porphyry deposit was chosen to compare results (Sample Z). Sample Z was visually logged to have abundant carbonate 60%, quartz 30% and minor chlorite 10%.

3.1   Hyperspectral Evaluation

Hyperspectral qualitative mineralogy for Sample Z is displayed in Figure 3. Figure 3a shows the core sample as an RGB image. Figure 3b shows the carbonate spectral
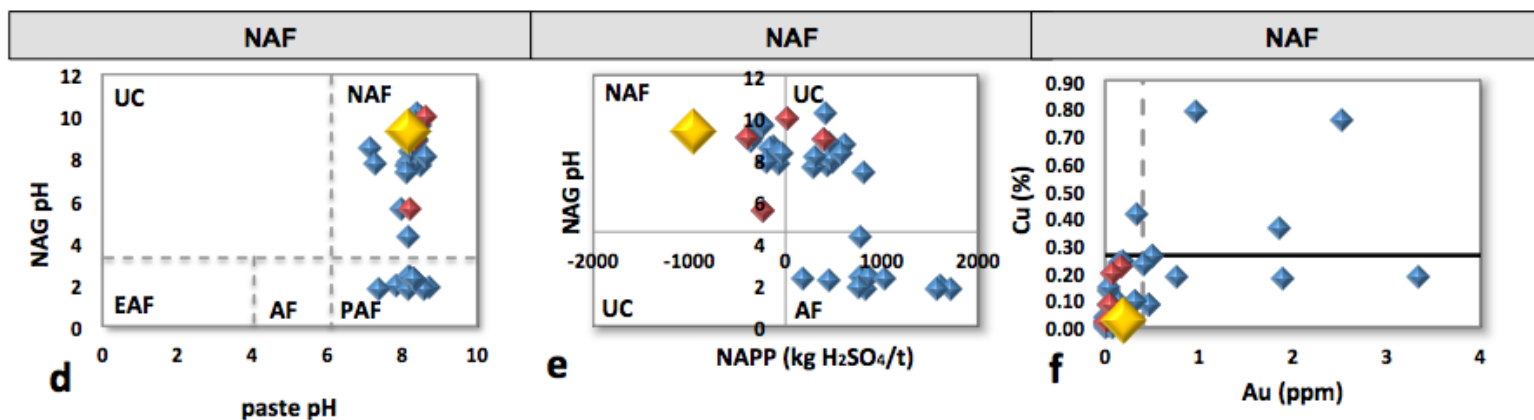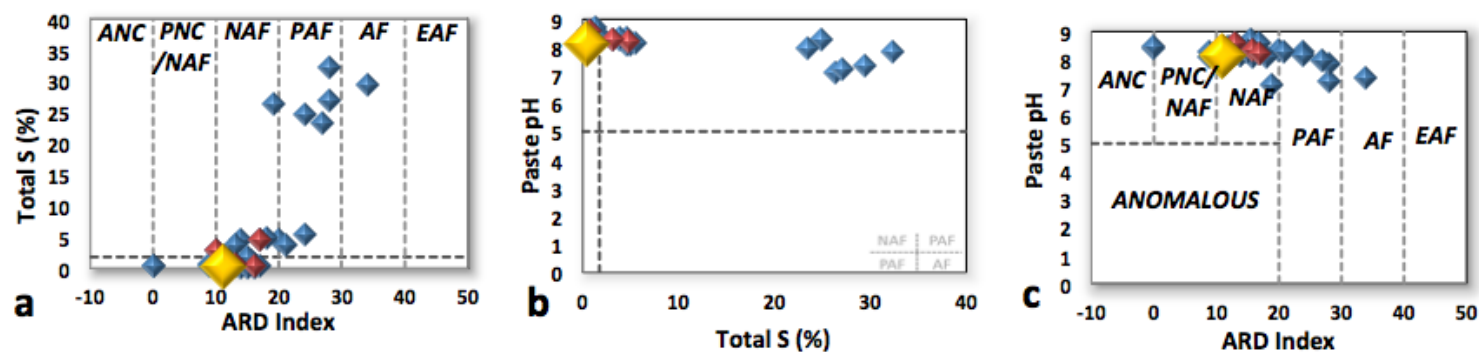
match. Warm colours (red, orange, yellow) indicate a high confidence between carbonate spectra recorded from analysis and carbonate spectra in the mineral library. Cool colours (green, blue) indicate a lower confidence between spectra recorded from analysis and carbonate spectra in the mineral library. Black shows no similarity between measured spectra and a match between carbonate. Figure 3c shows a Corescan® mineral class map. This represents identified mineralogy on a colour scheme. Sample Z shows a high abundance of carbonate throughout the sample. Corescan® calculated relative mineral abundance are displayed (Figure 3d). Aspectral, carbonate, quartz and sericite dominate (36.9%, 34.4%, 16.6% and 6.1% respectively). Semi-quantitative bulk mineralogy data from XRD are displayed for Sample Z (Figure 3e). Carbonate, quartz and chlorite dominate (56.3%, 28.7%, 4.7% and 4.4% respectively). The calculated GDI for Sample Z is 343.68, which is categorised as low risk (Table 3).

3.2 Geochemical Characteristics

Geochemical data were compiled into an interactive dashboard. Through this tool, all geochemical data can be displayed and easily compared. Each graph is then automatically scored and labeled according to the predetermined category (i.e., NAF = non acid forming). Figure 4 is an example of the interactive display page of the dashboard. Data displayed corresponds to sample Z. Figure 4a – 4e (S Total vs acid rock drainage (ARD) index, Paste pH vs S Total, Paste pH vs ARD Index and NAG pH vs paste pH) show that geochemically Sample Z is non-acid forming (NAF) and the sample is below economic grade (Figure 4f).
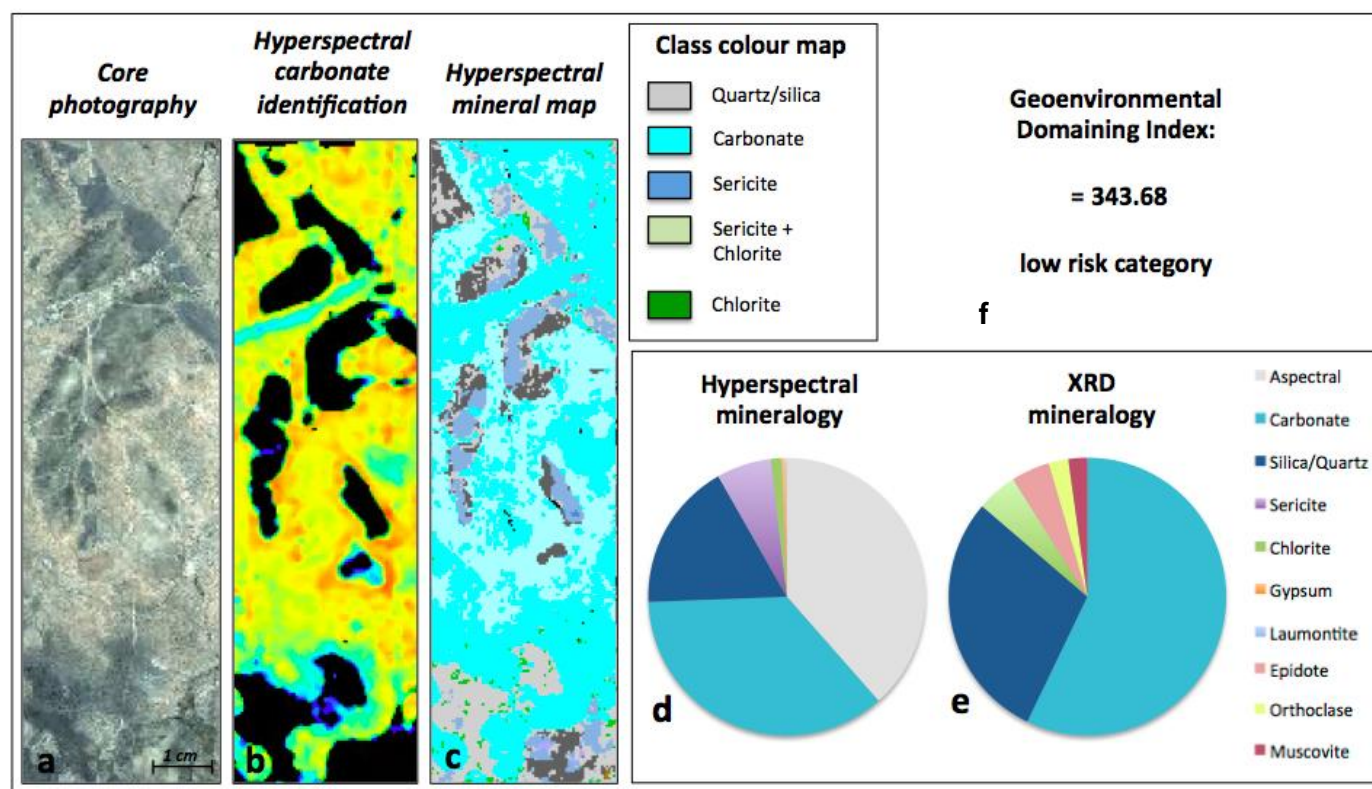
Figure 3. Mineralogy results for sample Z. a, b and c show qualitative hyperspectral mineral outputs: RGB core photography, hyperspectral carbonate identification and hyperspectral mineral map respectively; d displays relative hyperspectral mineral abundance; e shows XRD semi-quantified mineralogy and f shows the overall GDI classification.

a — Total S (%) vs ARD Index. Regions labelled: ANC, PNC/NAF, NAF, PAF, AF, EAF.

b — Paste pH vs Total S (%). Regions labelled: NAF | PAF, PAF | AF.

c — Paste pH vs ARD Index. Regions labelled: ANC, PNC/NAF, NAF, PAF, AF, EAF, ANOMALOUS.

| NAF | NAF | NAF |

d — NAG pH vs paste pH. Regions labelled: UC, NAF, EAF, AF, PAF.

e — NAG pH vs NAPP (kg H$_2$SO$_4$/t). Regions labelled: NAF, UC, UC, AF.

f — Cu (%) vs Au (ppm).

| NAF | NAF | Below grade |

Legend
- ◆ All data
- ◆ Alteration class
- ◆ Current sample

Acronyms

ANC	Acid Neutralising Capacity	EAF	Extremely Acid Forming
PNC	Potential Neutralising Capacity	ANOMALOUS	Requires Retesting
NAF	Non Acid Forming	UC	Uncertain
PAF	Potentially Acid Forming	ARD	Acid Rock Drainage
AF	Acid Forming		

Geoenvironmental risk evaluation dashboard

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384

Figure 4. Geochemical dashboard display of two drill holes *(n = 30 samples).* **The yellow diamond represents example Z, the red diamonds represent samples from the same alteration type and the blue diamonds represent all data. Specific values for sample Z: total S, 0.3%; ARDI value, 11; Paste pH, 8.1; NAG pH, 9.3; NAPP, 963 Kg H_2SO_4/t; Cu 0.02% and Au 0.2**

3.3 Comparison of GDI and Geochemical Characteristics.

NAG pH vs Paste pH classification show that a large proportion of samples analysed is NAF (Figure 5). NAG pH values range from 1.8 to 10.2 with a distinct NAF population pH 8. This graph demonstrates that it is difficult to use geochemistry alone to distinguish between NAF and ANC material. However, comparisons between the GDI and NAG pH show that discrimination could be possible (Figure 6). It also shows that NAG pH values compared to mineralogy could help identify high and moderate ANC material, especially when combined with classifications from Table 3.
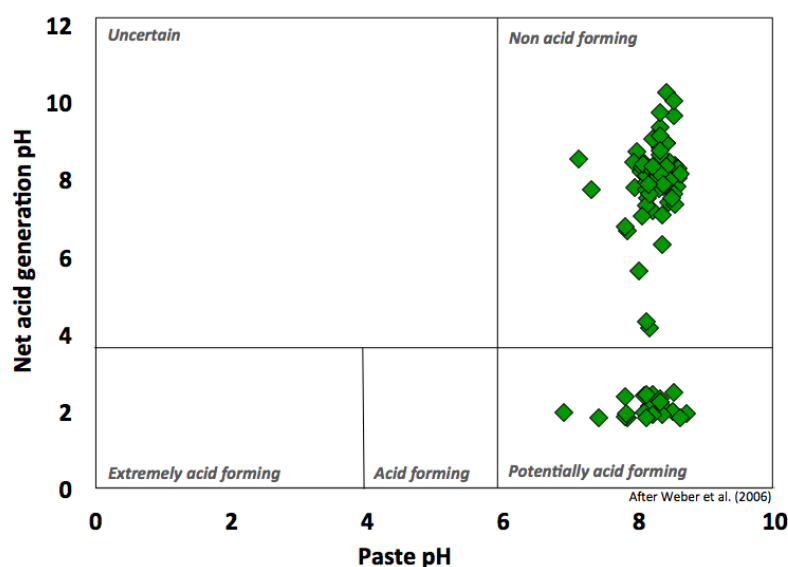

Figure 5. NAG pH vs Paste pH plot *(n= 100),* **after Weber et al. (2006).**
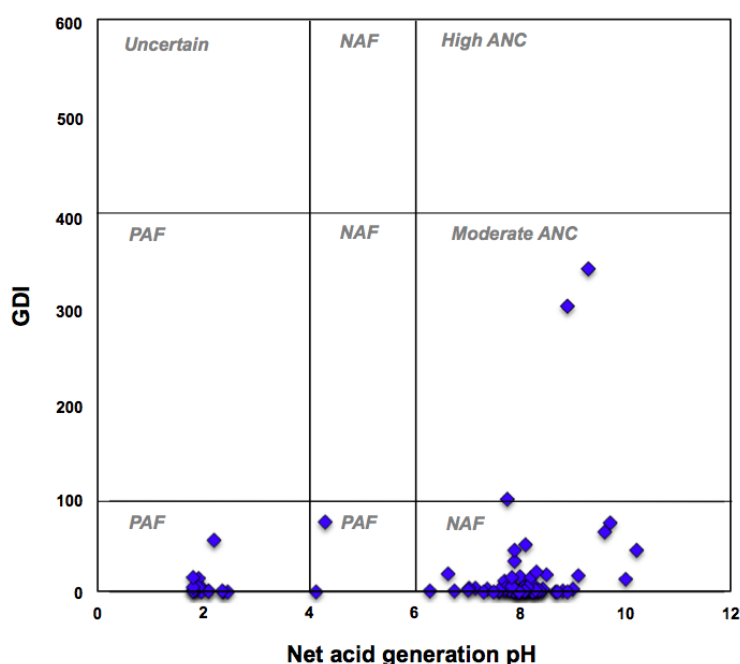

Figure 6. GDI vs NAG pH plot *(n=100).*

4.0   DISCUSSION AND CONCLUSIONS

When used correctly, industry geochemical tests are able to accurately predict acid and metalliferous waste material (e.g., Windy Craggy; Morin and Hutt, 2001; Macraes gold mine; Schroeder et al., 2005; Pebble porphyry deposit; Harraden et al., 2013). While these geochemical, geological and mineralogical tools can discriminate between acid forming and neutralising capacity of mine waste, they have limitations and can easily be misused. Limitations of these tests are well documented in literature (e.g., Parbhakar-Fox and Lottermoser, 2015 and Dold, 2016) and can include compounding laboratory errors, as well as being consuming of both time and cost. Inadequate geological and mineralogical understanding of waste material including inappropriate testing and misinterpretation of available data can compromise effective mine waste planning, storage design and management (Wei et al., 2013). Recently, Parbhakar-Fox et al. (2017) demonstrated how new techniques of blended static testing holds opportunities to improve first pass waste-rock handling practices and waste pile design. Thorough up front waste characterisation like this is vital, as neutralising minerals are not always available when required or accessible in mined waste or in the waste storage facility, and can be costly to import. The imperative importance of neutralising material is being recognized, as an increasing number of studies are looking outside of the mining industry for solutions. Monte et al. (2009), Mäkelä et al. (2010) Mäkitalo et al. (2015) and Mäkitalo et al. (2016) all investigate the integration of solid residues from steel, pulp and paper industries with mine waste as alternate management methods. However, by identifying inherent neutralising materials on site, one could maximise resource value by making use of all materials (not just ore) and minimising waste. Incorporation of tools that can rapidly and correctly discriminate NAF from ANC material during early LOM is a critical missing step.

Differentiation of waste material using only ABA does not always lead to AMD prevention or allow for detailed mineralogical interpretation or classifications. Examples of failures to predict and prevent acid formation can be found throughout the literature (e.g., Morin and Hutt, 2001; Akcil and Koldas, 2006; Nieto et al., 2007; Rao et al., 2017). Furthermore, lack of mineralogical understanding can result in inappropriate test choices when deciding which geochemical procedure to follow. For example, Parbhakar-Fox and Fox (2017) noticed differences in reported NAG pH values when using 30% H_2O_2 as opposed to 15% H_2O_2 on samples with high wt. % sulfide (i.e., >2 wt.%). When the post NAG powders were analysed under Scanning Electron Microscopy (SEM), it was noticed that sulfides were not completely oxidised. Similarly, Noble and Lottermoser (2017) found significant inconsistencies in pH values of standards through a range of geochemical tests (e.g., paste pH and NAG pH). These examples highlight the need for caution when selecting and undertaking geochemical testing and when interpreting results. In addition, Villanova et al. (2017) states that, in order to correctly define representative samples and proper analytical techniques, you must fully understand the mineralisation. Therefore using mineralogy to guide testing, such as NAG tests, can only improve reliability, reproducibility and confidence in undertaking testing and in reporting. This study has shown that mineralogy collected through hyperspectral core logging can quickly and reliably provide semi-quantified data useful to inform geoenvironmental testing. In addition, using Coreshed, while undertaking traditional core logging, can help maximise logging effectiveness, remove subjectivity, produce more accurate and detailed logging data bases and aid with sampling (e.g., Figure 1, 2 and 3).

Statistically, sampling campaigns often fall short of adequately assessing best practice sample numbers as recommended in Price (2009). As a consequence, the accuracy of waste management planning is likely to be reduced, increasing the potential for environmental risk later in the LOM. Parbhakar-Fox and Dominy (2017) argue that the

importance of sample selection cannot be underestimated. They suggest sample selection is the single most critical aspect of any geoenvironmental investigation. Inadequate comprehensive sampling before commencement of mining could therefore contribute to excessive variance, difficulties in interpretation and incorrect assessment of results. Observations from Dominy (2017) in gold grade variability were enhanced by poorly designed sampling and testwork protocols. He argues that testwork throughout the mine value chain must be supported by high-quality representative samples. These comments not only apply to gold mining but also to environmental sampling. Optimisation processes must consider geological/mineralogical nature of ore type(s) and likely domains (Dominy, 2017).

Rapid mineralogical mapping tools can provide qualitative and semi-quantitative mineralogical data, improving speed and accuracy and removal of the subjective nature of traditional core logging. There is also a large potential for this type of technology to be used to classify mineable waste domains reliably, be able to direct sampling campaigns at deposit scale and therefore improve waste storage design and minimise AMD. This study used Coreshed for mineralogical domain-driven sampling on five drill holes (Figure 2). Sampling using this method dramatically increased confidence, reproducibility and modeling of geochemical data, as opposed to random sample selection used on two the other drill holes. Utilising drillcore mapping tools to domain waste, focus sampling and determine mineralogy before geochemical testing can ensure certainty in testing results, confidence in propagating those results across a larger domain, allow construction of a larger comprehensive deposit scale waste characterisation datasets and hence a fully-inclusive planning tool.

Development of the GDI utilising hyperspectral data has proven to be a valid domaining tool for characterising potentially neutralising material. It is able to rapidly incorporate all mineralogy and give a quantified number relevant to a risk category (Table 2 and 3). Fast hyperspectral data collection speeds (2 km drill core/day) can allow for rapid geoenvironmental domaining of large areas. This can allow for targeted sampling campaigns (Figure 2) and lead to better overall waste forecasting. Initial results show that mineralogy-driven domaining of this sort corresponds well with standard geochemical testing (Figure 3 and 4). The advantage of utilising hyperspectral data gives complete downhole assessments as opposed to point sampling. It also incorporates ANC from all minerals (e.g., Table 2). It allows for a robust estimate by including all carbonate and silicate mineralogy. Additional incorporation of relative reactivity values provides an indication of potential neutralising capacity when exposed to acidity generated by oxidation of sulfides. Integration of the GDI with other techniques to give mineral chemistry (such as, LA-ICPMS) can lead to best practice waste rock assessment and waste planning.

The GDI, as it stands, does not include mineralogical influences endemic to acid forming minerals. Improved sulfide recognition on hyperspectral platforms would allow for improved domaining. Deposit scale assessment of all materials, categorising ANC, as well as AF and PAF, material could have a large impact in the way sampling campaigns are undertaken, deposits are mined, scheduling of material and waste rock pile design. Further work includes improving sulfide identification to allow for acid producing potential inclusions into the GDI. Kinetic testing (current run time = 23 weeks; scheduled run time = 60 weeks to fit with project timeline) has been established to investigate robustness of waste domaining using the GDI.

The lack of long-term consideration for the whole LOM and the inherent instability of mining projects contribute significantly to irreversible mineral losses and resource sterilization (Lèbre et al., 2017). Lèbre et al. (2017) suggest further research should address the identification of practices and strategies that (1) anticipate for future use

of material beyond the closure of a mining project or (2) contribute to making mining projects economically viable in the longer term. The movement towards more sustainable practices in mining is exponentially increasing. Utilisation of technologies such as hyperspectral mineral identification can assist in improvements for rapid mineral identification and subsequently geoenvironmental sampling and domaining.

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