

Effective Field-Based Testing Tools for Rapid ARD Prediction

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ABSTRACT

Accurate prediction of acid rock drainage (ARD) during early life-of-mine stages is critical for the development of effective waste management strategies. However, tests and methodologies used by industry focus on the extensive use of geochemical tests i.e., those associated with acid base accounting. Due to the high costs and turn-around time of such tests, only a limited number of samples are selected for predictive testwork. Consequently, detailed ARD characteristics of a deposit cannot be understood, resulting in the development of inadequate waste management plans and rehabilitation strategies. Instead, industry requires effective tools and protocols which allow for a greater number of samples to be evaluated, and are simple enough to perform in a field-laboratory, thus keeping costs to a minimum and turn-around time short. To satisfy such requirements, simple field-based pH tests should be utilised. In addition, methods to improve mineralogical characterisation in drill core materials should be employed including an ARD focused logging code, chemical staining and the use of portable instruments (i.e., portable XRF, Equotip). Finally, methods for evaluating geometallurgical data for ARD prediction should be used, and have real potential to add-value to existing datasets.

These new tools and protocols were developed and tested using drill core and waste rock materials obtained from several Australian mines with differing geology, mineralogy and mineralisation style. Our research shows that by adopting these improved tests and methods, the industry will be able to: i) perform effective predictive ARD testwork; ii) achieve detailed deposit-wide characterisation, iii) develop the best possible waste management plan; and iv) evaluate only the most suitable rehabilitation options.

Keywords: management, geochemical, prediction, waste rock, test

INTRODUCTION

Oxidative dissolution of sulphidic minerals present in mine waste materials (e.g., waste rock, tailings) has the potential to release acidic leachate (acid rock drainage, ARD), sulphate and potentially deleterious elements e.g., As, Ag, Cd, Cr, Cu, Hg, Ni, Pb, Sb, U and Zn. Therefore, in order for mining operations to adequately control and manage ARD during the entire life-of-mine, a comprehensive approach to ARD prediction must be adopted, benefits of which will be minimisation of environmental impacts, and reduction of financial liabilities associated with closure. Such an approach requires: i) analysis of an adequate number of samples, and ii) a short turnaround time frame in which to collect pertinent ARD data to allow for basic waste classification. The current industry approach to ARD prediction relies upon using geochemical tests (e.g., static, kinetic). However, limitations of static testing have long-since been established (i.e., the use of sulphide-sulphur vs. total sulphur in calculation of maximum potential acidity (MPA), variations in reaction times and chemicals in acid neutralising capacity (ANC) experiments). Furthermore, kinetic tests run for a minimum of 30 weeks i.e., data returned too slowly to guide development of an adequate waste management strategy. Most significantly, neither static nor kinetic testwork are suitable to perform on regulator recommended number of samples for ARD testwork during early life-of-mine stages (e.g., several hundred; Australian Government, 2007) due to the costs involved. For example, a basic net acid producing potential (NAPP) and net acid generating (NAG) package costs A\$50 (Australian Laboratory Services, 2014) and can take at least 5 days (on sample receipt) for data to be reported. Performing such screening tests on best practice number of samples (e.g. 500 samples) would cost at least A\$25,000, excluding sample preparation and handling costs. Additional mineralogical testwork would likely be required (average cost per sample: A\$50-150), and any further geochemical testing (i.e., sulphide-sulphur determination, pH testing, advanced NAG tests) would result in significant financial expenditures.

Ideally, industry needs to have a field-appropriate ARD prediction toolbox that allows useful data to be collected more time-efficiently and cost-effectively. If such tests can be readily performed at mine sites, then samples for more detailed ARD testwork (i.e., using the established methods) can be better chosen. Considering this, we have evaluated several test methods (both geochemical and mineralogical) for rapid field-based ARD prediction. These included: i) chemical staining to identify neutralising potential, ii) field-based pH testing, iii) field portable instruments and iv) ARD focused logging. All results were validated against established methods e.g., X-ray diffractometry (XRD), X-ray fluorescence (XRF), and static tests (total-sulphur, multi-addition NAG and Sobek methods). These methods were tested using drill core and waste materials collected from several Australian mine sites, including two operational volcanogenic massive sulphide deposits located in Western Tasmania, and one abandoned lode gold deposit located in Queensland. Examples from these studies are presented in this paper.

METHODOLOGY

Both drill core and waste rock samples were collected from three sites (1, 2 and 3) between 2007 and 2013. Site 1 is an operational polymetallic volcanic-hosted massive sulphide deposit located on the western coast of Tasmania. Site 2 is an abandoned lode-Au mine operations in Queensland where the dominant waste rock lithologies comprise hydrothermally altered rhyolite/ rhyolite tuffs which host sulphide bearing quartz lodes. Site 3 is a deposit part of the large Cambrian hybrid volcanogenic-magmatic Cu-Au-Ag system at Mount Lyell, Western Tasmania.

Sample preparation

Each sample from site 1 and 2 was sawn in two to allow for photography and logging of a fresh surface. One portion was subjected to crushing and milling to <63 µm for geochemical and mineralogical testwork. The other portion was kept intact for mineralogical and chemical analyses using stains and field-appropriate equipment. Drill core from site 3 were first subjected to chemical staining and geometallurgical testwork, followed by the selection of representative samples every 1 m for validation geochemical and mineralogical analyses. These samples were also crushed and milled to <63 µm.

Chemical staining

Chemical staining techniques are under-utilised in the mining industry despite being simple and inexpensive tools to distinguish mineralogy and texture in a range of sample types (i.e., drill core, grain mount and thin section). Various carbonate staining techniques exist as published by Freidman (1959), Warne (1962) and Reid (1969). The methods presented in Freidman (1959) were used in this study as these are the most commonly used (Hitzman, 1999). The advantage of using chemical stains on drill core is that carbonate materials (particularly effective neutralisers such as calcite and dolomite) can be confidently identified, thus allowing for improved estimations of their modal abundance during logging or initial ARD assessments.

All drill core samples (n= 51- site 1; 70 m - site 3) were subjected to staining. Prior to staining, drill core materials were etched with dilute hydrochloric acid (HCl) for 2 to 3 minutes, and subsequently washed with water. Samples were then left to dry for approximately 30 minutes. Site 1 samples were placed directly in a plastic container containing the stain and left to soak for approximately 15 minutes in a dual stain comprising the organic dye Alizarin red-S (ARS) and potassium ferricyanide (PF) dissolved in HCl. For site 3, samples were stained directly with the same stain using a paintbrush. The ARS produces a pink to red stain on any carbonate that will react with dilute acid. The more reactive carbonates such as calcite and aragonite stain red, but the less reactive such as dolomite and siderite, remain unstained (Friedman, 1959; Hitzman, 1999). Whilst pure dolomite does not stain, if iron is substituted into the dolomite lattice, it becomes more reactive thus; ferroan dolomite and ankerite stain with ARS (Hitzman, 1999). The PF stain is more effective at identifying ferrous carbonates, as it reacts with ferrous iron causing a precipitate of Turnbull's blue to form (Dickinson, 1966). Siderite does not react with this stain. Therefore where zones of high acid neutralising capacity (ANC) are reported, but no staining colour is observed, the effective ANC can be considered low as siderite is not an effective carbonate neutraliser. After staining, samples were imaged to allow for comparison against unstained images.

Environmental logging

Textural analysis is largely absent from predictive acid rock drainage (ARD) assessments despite the direct control of texture on acid formation as discussed in Parbhakar-Fox et al. (2011). Motivated by this, these authors developed the 'ARD Index' (or ARDI) which allows for simple textural evaluations to be performed. The generated ARDI values are recommended for use in conjunction with sulphur assay or paste pH data to domain ARD forming potential. The ARDI proposed by Parbhakar-Fox et al. (2011) required assessments to be performed on both a mesoscale and microscale. However, a modified ARDI has since been developed for site 1 to allow for the performance of simpler, more time efficient assessments. An assessment was performed on all

samples, over an 8.5 cm x 5.5 cm size area, with the area most dominated by sulphide chosen for assessment, as the most conservative ARDI value was sought.

Field pH testing

Paste pH testing represents the most efficient manner by which to assess a sample's immediate acid forming characteristics. Considering this, it was performed on all samples at the University of Tasmania (UTas, School of Physical Sciences, CRC ORE laboratory), with the ASTM D4972-01(2007) method used on drill core materials (i.e., site 1 and 3) following recommendations given in Noble et al. (2012). For weathered materials from site 2, the AMIRA P387A Handbook method (Smart et al., 2002) was used. The pH value of each tested sample was measured in triplicate, with the standard deviation calculated as <0.5.

A method to accelerate the paste pH test by using a hot electrolyte solution to encourage faster reaction kinetics was trialed. Select pulverised (< 63 µm) materials from sites 1 and 3 (n=20) were paste pH tested using three different electrolyte solutions: i) tap-water; ii) deionised water (DI); and iii) 0.01M CaCl₂. Certified reference materials KZK-1 and NBM-1 (purchased from CANMET; Natural Resources, Ottawa) were also tested. These solutions were heated to 100°C and poured onto 10 g of sample weighed out in 50 ml glass beakers, with a 1:2 solid: solution ratio used. Once poured, beakers were stirred for 30 seconds and allowed to cool to room temperature. Measurements of pH and EC were taken after 1 hour in triplicate, with standard deviation calculated as <0.01.

Field instrumentation

Short-wave infrared

The application of short-wave infrared (SWIR) spectroscopy in determining pale, fine-grained alteration minerals has been demonstrated in ore-deposit characterisation studies (e.g., Thompson et al., 1999; White et al., 2010). Mineral identification is based on absorption spectra collected from clean, dry, flat, rock surfaces (Gifkins et al., 2005). SWIR therefore has potential to improve mineral identification of altered drill core samples for ARD characterisation. Two instruments were selected for testing in this research on samples from site 2; a portable infrared mineral analyser (PIMA; manufactured by Integrated Spectronics, Australia) and a TerraSpec spectroradiometer (manufactured by analytical spectral device (ASD) Inc.). Materials from site 3 were tested using the TerraSpec only, however in this study, both intact pieces and homogenised powders from each 1 m interval were analysed to assess which is a more appropriate sample type.

Portable XRF

Accurately measuring chemistry and comparing these data to ARD parameters (e.g., paste pH, total-sulphur) allows for a first-pass indication of potential leachate quality issues which may arise towards the life-of-mine end (i.e., mine closure). This in turn allows the development of appropriate waste management plans. Field-portable XRF (pXRF) instruments have in recent years been used in mine site characterisation studies for determining element concentrations (e.g., Haffert and Craw, 2010; Higuera et al., 2012). Most recently, Parbhakar-Fox et al. (2014) discussed its application in mesotextural classification at abandoned mine-sites. In this study, a hand-held Olympus-InnovX instrument was used (UTas, School of Earth Sciences) on intact drill core (three

areas selected) and homogenised powders at site 1, and powders taken at 1 m intervals at site 3, with reference standards NIST 2781, GXR3-538 and GXR4-2843 used throughout the analyses. A benchtop Innov-X X50 XRF instrument was used to analyse waste materials collected from site 2. Both homogenised powders and intact portions (three areas analysed) were tested in this particular study. The instrument was routinely calibrated by the material supplied by the manufacturer during the analyses (i.e., after every 10th measurement).

Equotip

Measuring the susceptibility of a lithology to weathering is required to understand how rapidly acid forming minerals will become exposed in a waste rock pile. Therefore, the application of Equotip (a non-destructive, core-based measurement technique) which measures hardness was explored. The Leeb (Ls) hardness value (0 to 1000) is automatically calculated, and is the quotient of the rebound velocity over the impelled velocity multiplied by 1000 (Keeney, 2008). The impact body rebounds faster from harder test samples than it does from softer ones, resulting in a greater value. Approximately 3000 Equotip measurements were collected on site 3 material only, using an Equotip 3 (Proceq) instrument, across the whole 70 m interval. Average values were calculated for each 1 m interval based on measurements taken at 2.5 cm intervals. These values were used alongside total-sulphur values for comparison with NAG pH vs. paste pH data. This has the potential to allow for a low-cost first-pass understanding of lag-time to ARD on a deposit-scale.

Geochemical and mineralogical validation testing

Rapid and accurate measurement of total sulphur (wt.%) for comparison against Equotip and calculation of maximum potential acidity (MPA) was performed on samples from sites 1 and 3 using an Eltra C-S 2000 instrument at UTas (School of Physical Sciences). For site 2 samples, total sulphur was measured using a Thermo Finnigan 1112 Series Flash Elemental Analyser instrument (Central Science Laboratory (CSL), UTas). Appropriate standard materials were analysed on both instruments during all analyses. In addition, the total element chemistry of samples from site 2 was measured for comparison against pXRF data using a Philips PW1480 X-ray Spectrometer (UTas, School of Physical Sciences). Acid neutralising capacity (ANC) was measured by the Sobek method at ALS Brisbane for samples from all three sites. The multi-addition net acid generation (mNAG) test was performed on materials from all sites at UTas (School of Physical Sciences) following the AMIRA P387A method (Smart et al., 2002).

Mineralogical determination of material from sites 1 and 3 was performed using a benchtop Bruker D2 Phaser X-ray diffractometer at UTas (School of Physical Sciences). Mineralogical analyses for samples from site 2 were performed at the University of Ballarat, Australia, using a traditional Siemens D501 diffractometer.

RESULTS AND DISCUSSION

Domaining neutralising potential: staining

The dominant carbonate textures observed in drill core material from site 3 comprised of clasts (in limestone conglomerates) and veins. The Alizarin red S-potassium ferricyanide (ARS-PF) stain appropriately reacted with calcitic material in both textural forms; with the pink stain appropriately uptaken, with corresponding XRD data confirming this as calcite. Comparison of samples analysed

by the stain painted directly on, and those soaked directly in the stain, confirmed that stains were better uptaken by the latter method (Figure 1).

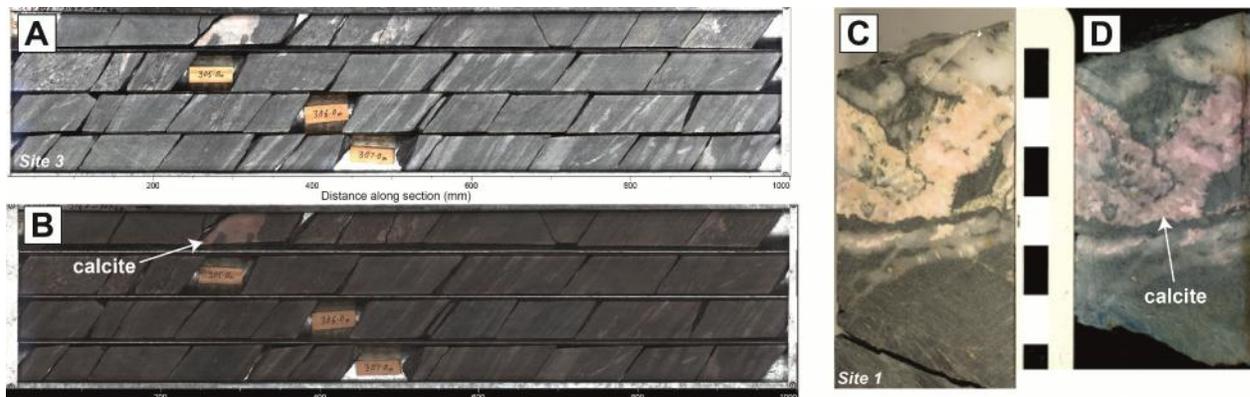


Figure 1 Photograph images of drill core from site 3 (massive sulphide deposit, western Tasmania, Australia);

A) unstained and B) after several coatings of stain were painted directly on; C) unstained drill core sample from site 1 (operational polymetallic mine, western Tasmania, Australia); C) stained drill core sample from site 1 after soaking in stain bath for 30 minutes. The pink colour seen in both examples indicates the presence of calcite thus identifying effective acid neutralising capacity

Domaining neutralising potential: SWIR

Whilst major rock forming minerals can be easily recognised in hand-specimen based on their different rock properties (i.e., hardness, lustre, habit), hydrothermally altered minerals are much harder to identify. Typically, they can appear as pale and fine-grained, and with such a grain size, potential for participating in neutralising reactions (cf. Plumlee, 1999) is much greater. As stated, homogenised powder samples from site 2 were used in a study to compare two commonly used SWIR instruments, namely the PIMA and TerraSpec. Muscovite was confirmed by XRD as the dominant alteration mineral in these hydrothermally altered rhyolite samples. Two examples of typical PIMA and TerraSpec results are shown in Figure 2. Spectra collected by TerraSpec (Figure 2b and d) were better defined (i.e., less noise), and show better agreement with the reference spectra. Results from PIMA showed greater deviation from the reference spectra for sample 1 (Figure 2a), and were aspectral from sample 2 (Figure 2b). Based on these results, the TerraSpec is given preference for use. Furthermore, the TerraSpec is not restricted to analysis of pale-coloured minerals like PIMA and can detect a greater range of minerals including iron-oxhydroxides.

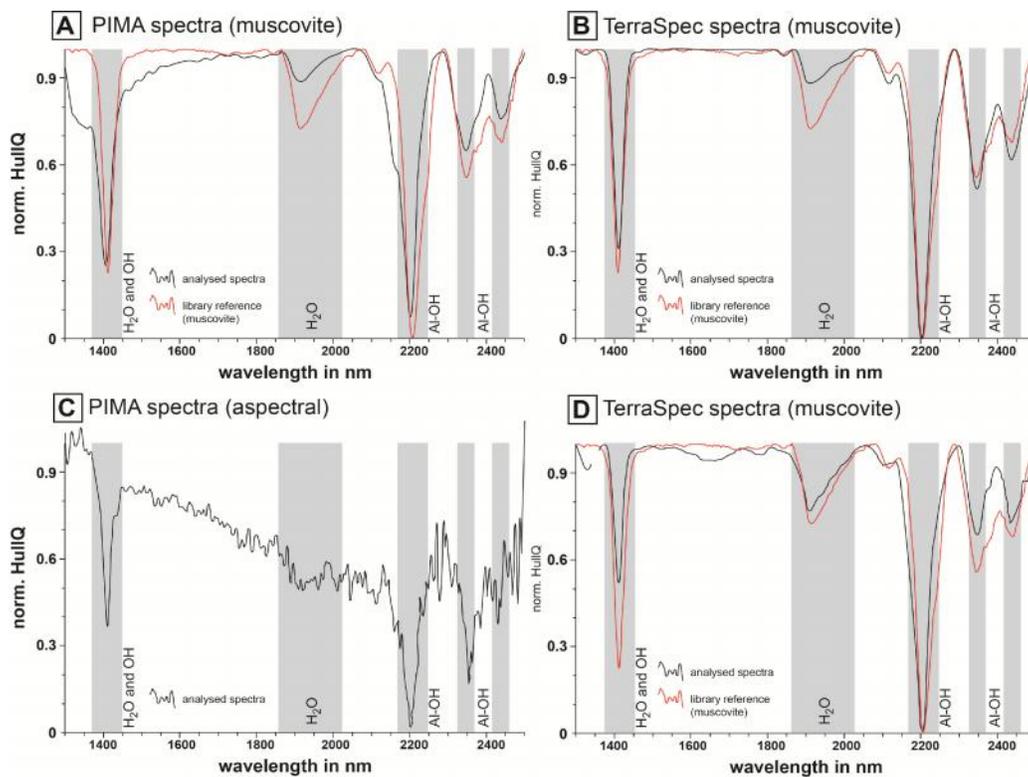


Figure 2 Example of alteration mineral identification in Site 2 (abandoned lode-Au mine, Queensland) waste rock materials; A) Sample A analysed on a PIMA with muscovite identified; B) Sample A analysed on a TerraSpec with muscovite confidently identified; C) Sample B analysed on a PIMA with an aspectral result; and D) Sample B analysed on a TerraSpec with muscovite confidently identified

In order to identify the best sample type for TerraSpec analysis, both powdered and intact drill core materials from site 1 were tested. For powdered samples, noisy spectra were collected, which were classified as aspectral, therefore, preference is given to using intact drill core. However, in validation testwork, the TerraSpec was less accurate than XRD. Whilst the TerraSpec was able to confidently identify the presence of calcite, muscovite and chlorite in 52% of the samples, it occasionally misidentified minerals such as tourmaline and epidote, which were neither logged, nor detected by XRD. Furthermore, whilst the TerraSpec instrument correctly detected the presence of carbonate minerals in 52% (i.e., identified as calcite) of these samples, the exact carbonate mineral type was only correctly identified in 10% of samples when compared to XRD. This is likely explained by having performed these analyses on intact drill core (i.e., non-homogenised, randomly selected areas for analysis); therefore there is a high likelihood of conflicts when compared to XRD data. Based on these results, it is evident that applications of TerraSpec for ANC domaining are limited.

Assessing acid forming characteristics

Paste pH measurements are shown in Figure 3 with data compared against NAG pH and total sulphur measurements as recommended in Parbhakar-Fox et al. (2011). A spread of data was seen for all sites. Site 1 samples were mostly classified as potentially acid forming to non-acid forming;

site 2 samples showed a range of classifications with both extremely acid forming and non-acid forming materials identified; and site 3 samples were potentially acid forming to acid forming.

Accelerated paste pH data (DI water, tap water and ASTM D4921-01) were compared against standard ASTM D4921-01 results for drill core materials from site 1 (Figure 4a) and site 3 (Figure 4b). In general, for site 1 the accelerated ASTM D4921-01 returned the lowest pH values by up to 2.3 units. Results from both accelerated water electrolyte experiments were in close approximation ($R^2=0.995$). However, when values were compared against standard ASTM D4921-01 method data, they were neither consistently higher, nor lower (pH unit difference range of +1.2 to -2.2). A similar trend was seen for site 3, with the accelerated ASTM D4921-01 test returning the lowest pH values for the accelerated tests. When these were compared against the standard ASTM D4921-01 method, an inconsistent trend was once again observed with a pH unit different range of +1 to -2.25. These results confirm that the accelerated test is encouraging reaction kinetics to proceed quicker as all accelerated values differ to the standard ASTM method. In order to understand the changes occurring during these tests, the supernatant chemistry will be assessed and a detailed XRD study of the residual powder will be undertaken. In addition, a re-evaluation of field-NAG tests is to be undertaken. The aim of this will be to produce a simple pH testing methodology (which can be performed at mine sites), the results from which can be used in more informative paste pH vs. NAG pH classifications.

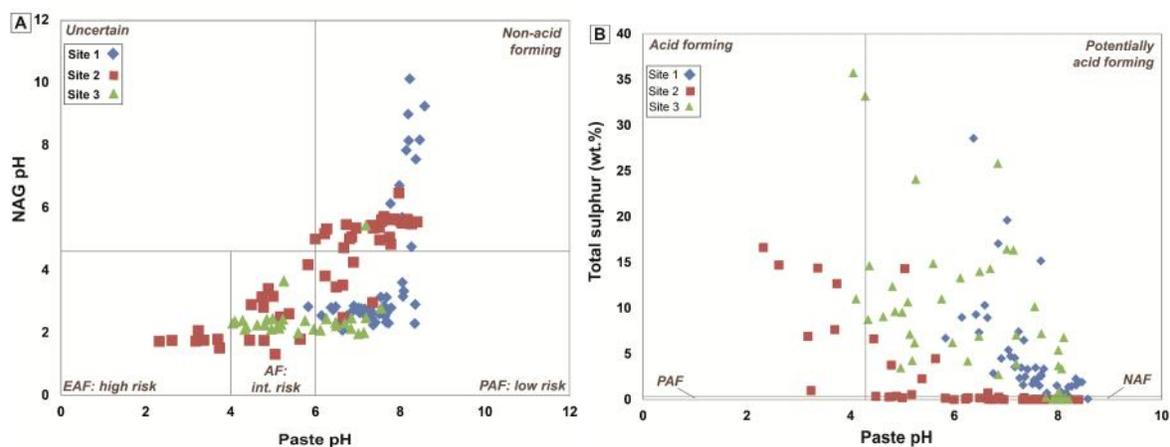


Figure 3 Paste pH measurements performed on drill core and waste materials from sites 1, 2 and 3; A) NAG pH compared against paste pH (after Weber et al., 2006); B) Total sulphur compared against paste pH (after Parbhakar-Fox et al., 2011). Abbreviations: AF, acid forming; EAF, extremely acid forming; PAF, potentially acid forming; NAF, non-acid forming)

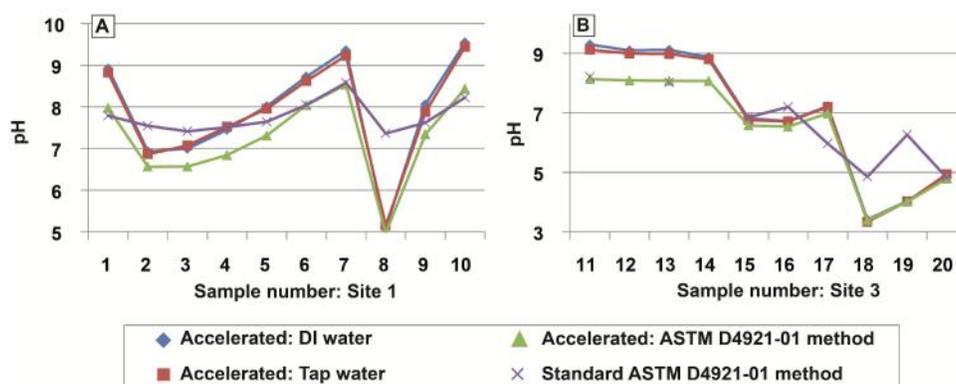


Figure 4 Paste pH test results for 10 samples from site 1 (operational polymetallic mine, western Tasmania, Australia; 1 to 10) and site 3 (massive sulphide deposit, western Tasmania, Australia; 11 to 21). Data from four experiments (3 accelerated, and one standard) are shown

Determination of bulk chemistry

Measurements of sulphur are essential for the calculation of MPA. However, the turnaround time for assay data may be significant (i.e., >48 hours). Alternatively, sulphur can be measured using a portable XRF or a benchtop element analyser. To test the accuracy of the various sulphur measurement techniques, materials from site 2 were subjected to measurements using an: i) element analyser; ii) traditional XRF; and iii) pXRF with results shown in Figure 5. Data from the element analyser and XRF were in close approximation ($R^2= 0.9979$), however, data from the pXRF was in less agreement when compared with both methods ($R^2= 0.886$ against EA; $R^2= 0.8197$ against XRF). Based on these results, the use of pXRF to directly calculate MPA should be avoided. Instead, this can be accurately determined using an element analyser (e.g., Eltra CS 2000 instrument), whereby reliable sulphur data can be collected efficiently. Instead, data from a pXRF instrument could be used to aid the identification of samples requiring such testwork, i.e., those with relatively high sulphur (i.e., above the specified total-sulphur cut-off).

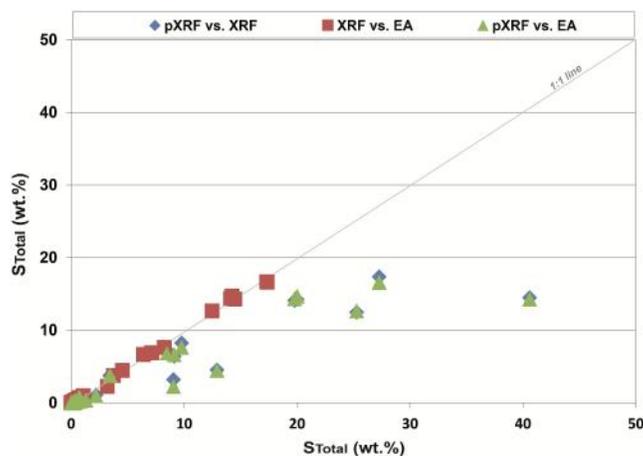


Figure 5 Total sulphur measurements made by three different analytical instruments (portable XRF, pXRF; XRF and an element analyser, EA) on samples from site 2 (abandoned lode Au-operations, Queensland, Australia)

The bulk chemistry was measured by XRF and pXRF for samples from site 2. Results for six elements commonly of environmental concern which were measured above detection limit are shown in Figure 6. Both techniques returned results in very close agreement (range of $R^2 = 0.9413$ for Sb, to $R^2 = 0.998$ for Pb). This indicates that element data collected from pXRF is relatively accurate, and therefore can be confidently used in classification schemes such as Ficklin plots (Plumlee, 1999). A similar conclusion as to the accuracy of pXRF instruments for waste classification purposes at the MacArthur River Mine, Australia was made by Landers et al. (2014).

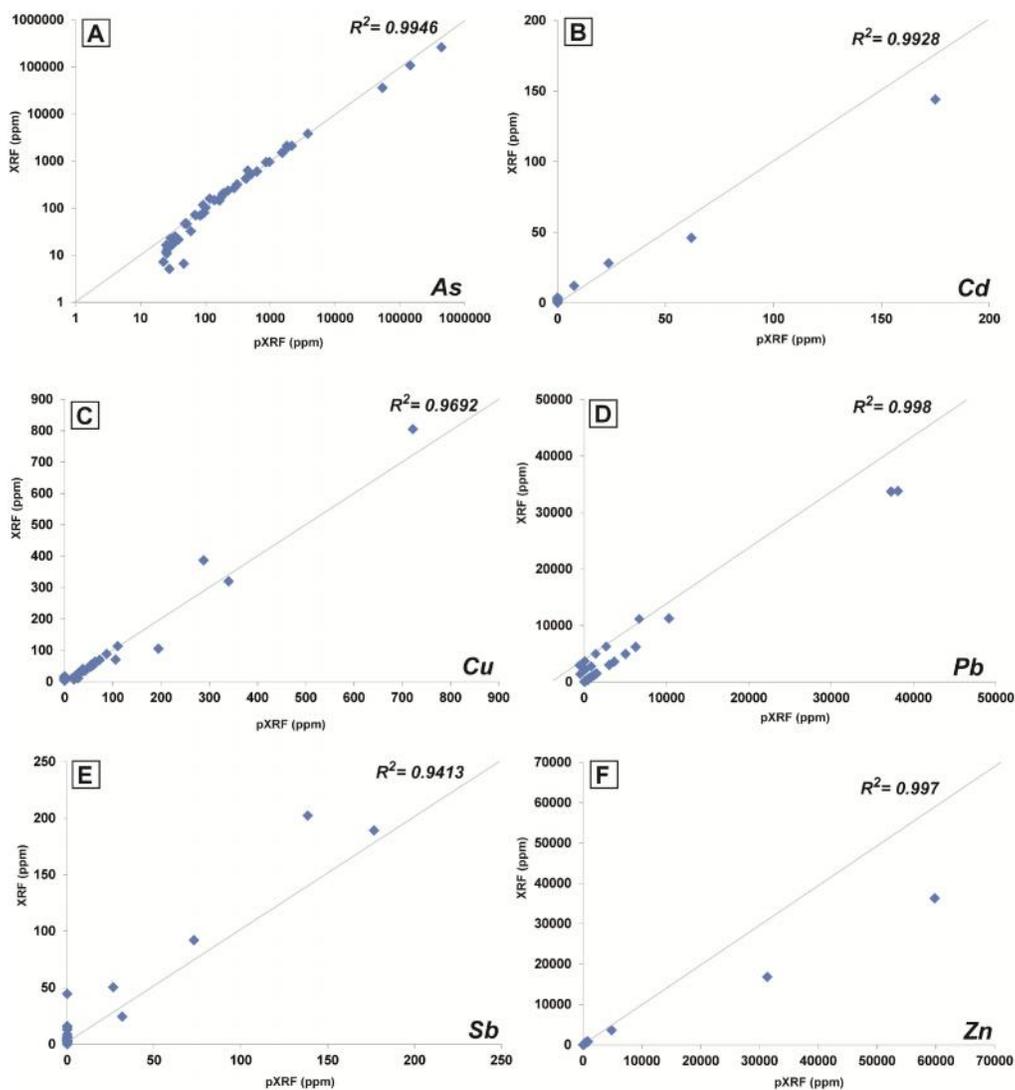


Figure 6 Concentrations (ppm) of selected elements: As (A); Cd (B); Cu (C); Pb (D); Sb (E); and Zn (F) measured in waste rock materials from site 2 (abandoned lode-Au, Queensland, Australia) by portable XRF (pXRF) and XRF techniques.

The type of sample to use in pXRF tests was evaluated using material from site 1. Both were homogenous powders and intact drill core were examined with results for the sum of metals (as considered in Ficklin plots) is shown in Figure 7. In general, there is positive correlation between both datasets ($R^2= 0.81$), with powdered samples generally returning higher values. From an efficiency perspective, collection of data on intact drill core is preferred; however, subjective (bias) sampling is introduced through identifying a particular interval for analysis. Furthermore, over a given interval (i.e., 1 m or 5 m), if one final value is to be utilised, how many analysis should be performed, and should an average value calculated and used? If analysis on drill core is to be pursued, a standard operating procedure must be enforced. To reduce such sampling issues, pXRF should be performed on powdered materials (again, it would be advantageous to use the same powdered materials as in total-sulphur and paste pH testing). In doing so, appropriate certified reference materials (CRMs) used here and described in Hall et al. (2014) and Piercey and Devine (2014) should also be analysed. Additionally, samples should be systematically selected for validation (using routine whole-rock analysis techniques) and if necessary, specific correction factors developed.

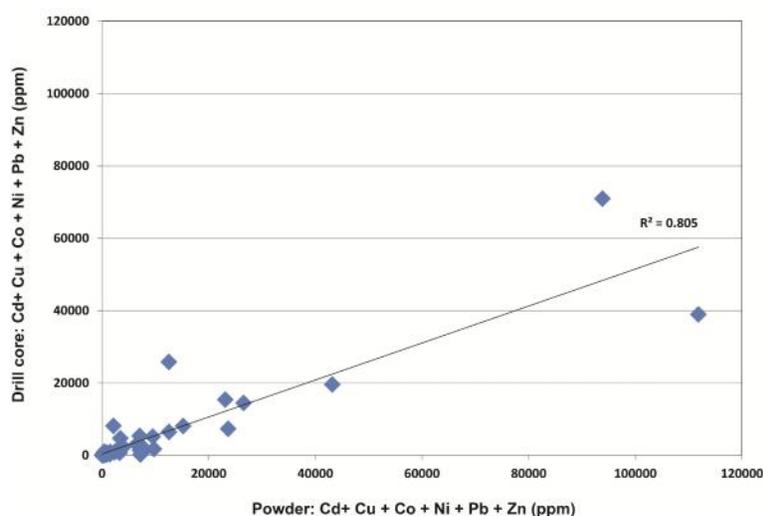


Figure 7 Total metal concentrations (Cd, Cu, Co, Ni, Pb, Zn in ppm) measured by portable XRF (pXRF) in drill core and homogenised powdered sample material collected from site 1 (operational polymetallic mine, western Tasmania, Australia, n= 51)

Using hardness for waste classification

Mineral hardness data was measured by Equotip for all drill core material collected from site 1 (304 m to 375 m). Whilst the objective was to domain ARD risk for the sulphidic schist material (345 m to 375 m), the Equotip data also allowed for ANC assessment for the carbonate-breccia material (304 m to 344 m). Comparisons of Equotip data against total sulphur and paste pH values are shown in Figure 8. If a mineral hardness value was <648 Ls, it was classified as soft in accordance with Keeney (2008). The schist material was classified as ‘PAF-rapid ARD likely’ by the criteria: paste pH <5.5, total-sulphur >0.3 wt. %, and < 648 Ls. Such a classification indicates that the material is susceptible to weathering as it is friable, which was observed in the field and during handling. Therefore, there is a greater likelihood of acid generation at a rapid rate, as sulphides in this material (i.e., pyrite and chalcopyrite) will be quickly liberated. These findings are in agreement

with the NAG pH vs. paste pH classification (Figure 3a). Materials were classified as having ANC by the criteria: paste pH ≥ 8 , total-sulphur values < 0.3 wt. % and < 648 Ls (e.g., 309 m to 315 m; Figure 8d). These were taken to represent the most effective neutralisers. This study indicates the potential assistance of Equotip data when performing field-based ARD studies. It is noteworthy that in the absence of paste pH data, mineral hardness and total sulphur data would have been sufficient to conservatively classify the behaviour of these materials.

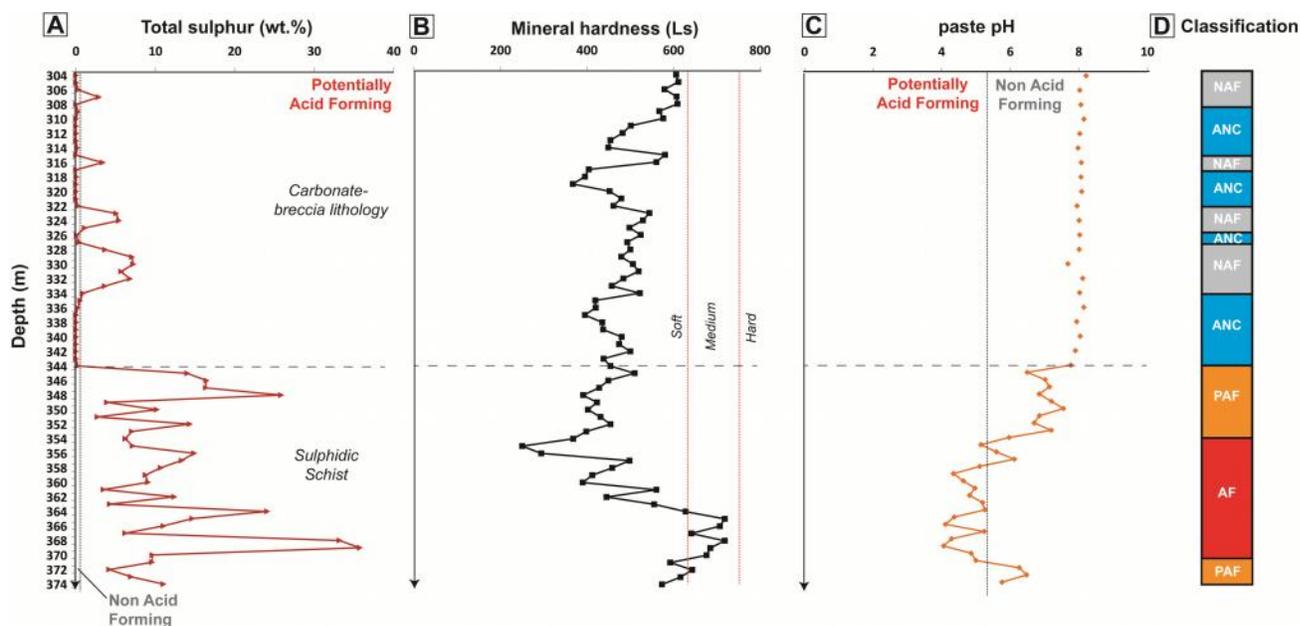


Figure 8 Downhole geochemical and geometallurgical data from site 3 (massive sulphide deposit, western Tasmania, Australia) drill core material (304 m to 375 m, change of lithology indicated by the horizontal dashed line at 345 m; A) Total sulphur values (wt. %; n=70) with 0.3 wt. % used as the classification cut-off criterion (Parbhakar-Fox et al., 2011); B) Mineral hardness values as measured by Equotip and reported in Leeb (Ls), with criteria for defining hard, medium and soft samples shown (Keeney, 2008); C) Paste pH values (n=55) with pH 5.5 used as the classification cut-off criterion; D) ARD classifications based on total sulphur, mineral hardness and paste pH values. Abbreviations: AF, acid forming, high risk with rapid ARD formation, ANC, acid neutralising capacity, highly effective; NAF, non-acid forming; PAF, potentially acid forming, medium risk with lag-time to ARD formation.

Geoenvironmental logging

A validation study of the acid rock drainage index (ARDI) was performed on drill core materials from site 1, whereby ARDI values collected in mesotextural scale drill core material only were compared against geochemical data (Figure 9). The ARDI was able to correctly identify samples with acid forming capacity (PAF, AF and EAF) when compared against total sulphur (Figure 9a), NAPP values (Figure 9b) and NAG pH (Figure 9c). The ARDI was more conservative in its classification of samples with neutralising capacity with several identified as NAF by the ARDI, but were identified as having an ANC by Sobek testing (Figure 9d). In this instance, the ARDI was

considered more accurate, as it evaluated the content of sulphides in proximity to, and the mineral associations of carbonate minerals. This study demonstrates the application of the ARDI, consequently, more mine sites should adopt such an ARD focused logging code in order to populate their mine database with this environmental attribute. Additionally, this method can be performed at mining operations in various stages of the life-of mine; for example: during exploration on hand specimen samples, during mine operations to check the correct placement of waste materials, and post-closure at historic or abandoned sites.

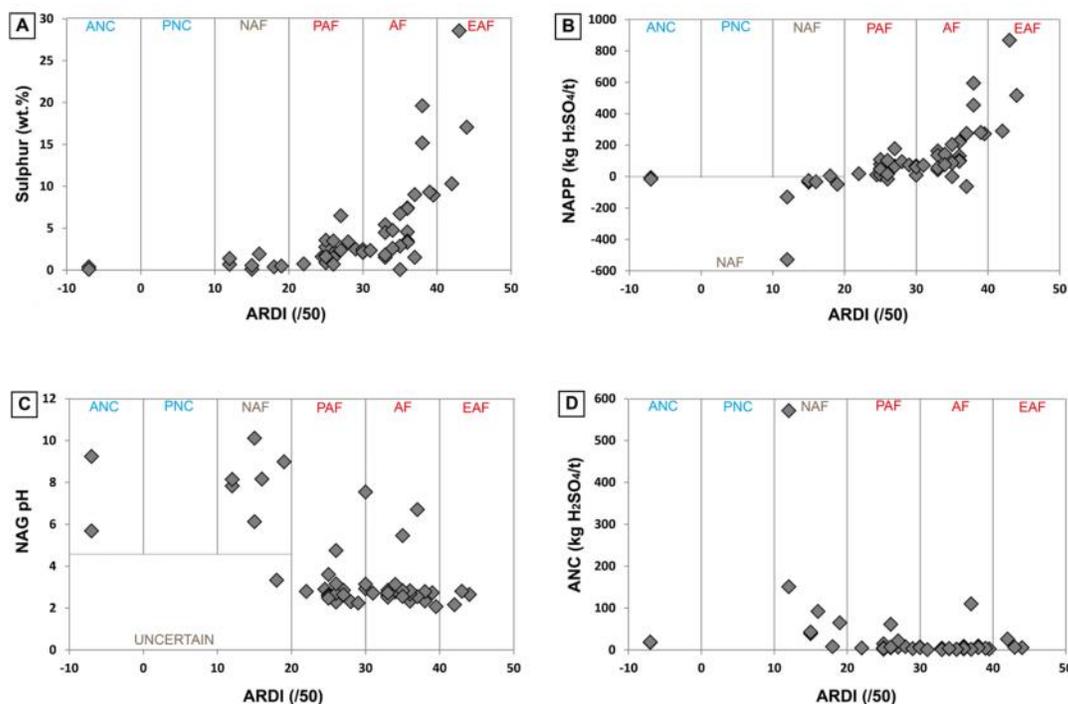


Figure 9 Comparison of acid rock drainage index (ARDI) scores given to site 1 (operational polymetallic mine, western Tasmania, Australia) drill core materials (n=51) against: A. Total sulphur (wt. %); B.net acid producing potential values (NAPP; kg H₂SO₄/t); C. net acid generation (NAG) pH; and D. acid neutralising capacity (ANC; kg H₂SO₄/t).

CONCLUSION

To effectively select the most appropriate samples for detailed geochemical and mineralogical test work, which allows for ARD prediction and waste classification during early life-of-mine operations, a pre-screening testing stage is required as described in Parbhakar-Fox et al. (2011). Such a stage must allow for a deposit-appropriate number of samples to be evaluated in order to build a database of ARD information allowing for the construction of a deposit-wide ARD model. Such a pre-screening stage must utilise efficient and cost-effective field-based tools. This permits site-based staff to characterise their own materials, thus reducing turnaround time for obtaining ARD relevant data, and improving the quality of decision making with regards to waste management (e.g., scheduling, handling and placement). A range of both existing and newly developed tools were examined in this study using materials collected from three Australian mine sites.

Our study indicates that chemical staining is an appropriate technique by which to identify the presence of carbonates if traditional mineral identification methods fail (e.g., if it is very fine grained and present in the rock matrix). Whilst the best stain responses are returned from soaking drill core directly in chemical stains, it may not be practical to perform in a field laboratory. Therefore, painting stains directly onto core gives sufficient results. Carbonate staining responses should be used to assist with environmental logging using a modified ARDI (i.e., mesoscale analysis evaluation only). The use of automated hyperspectral loggers (e.g., HyLogger) as used for geometallurgical testwork should be considered, as was demonstrated in Parbhakar-Fox and Lottermoser (2014). Short-wave infrared data collected by a TerraSpec instrument can be used to confirm the presence of carbonate but will only provide an indication of the exact carbonate mineral. Such analysis should only be performed on intact drill core materials and not on homogenised powders. In order to classify the geochemical behaviour of the materials, paste pH tests should be performed and used against portable XRF data (collected from homogenised powders) on Ficklin plots. However, paste pH testing must be standardised industry-wide, and methods in which to turn this simple method into a predictive test must be developed. The accelerated paste pH test represents one option; however, alternatives exist such as using a field NAG pH test. In addition, sulphur data should be collected on a bench-top instrument (if no assay data exist), and used with mineral hardness values (as collected by Equotip) and paste pH to domain lag-time to ARD.

The benefit of utilising these field-based techniques is that it enables a database of ARD data to be collected and held on site thus allowing for in-house expertise to be built up. Ultimately, this will lead to an improved quality of waste management strategies, and better forecasting of appropriate of rehabilitation options. Additionally, as demonstrated by using materials from site 2 (abandoned lode-Au operations, Queensland, Australia) these simple field-techniques can be used at mines in the final life-of-mine stage i.e., post-closure.

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