

# MANAGING ARD POTENTIAL THROUGH MINE PLANNING AND MINERAL PROCESSING PRACTICE

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## Summary

This paper suggests that the time is ripe for the development of a robust methodology for including acid and metalliferous drainage potential in the mine plan. This will be done by developing quantitative virtual and direct measures of drainage potential which have the necessary characteristics for inclusion in the block model of the mine. The methodology will lead to a more accurate valuation of the project, improved mine design, and optimal scheduling. There are sites where ARD potential is included in the block model now, but these are the exceptions rather than the rule, mainly through lack of an established methodology including sampling and testing protocols.

The enabling technologies needing development are mainly in the area of material characterisation, and use can be made of the very sophisticated automated quantitative mineralogy, textural and minor element instrumental methods now available.

This paper discusses the background to the problem, particularly in the context of a major research programme already underway to incorporate mineral processing attributes into the block model, which is likely to provide generic outcomes useful to the present objective. It considers the needs and methodology of mine planning, and critically reviews the current methods of testing for ARD<sup>1</sup> potential. A case study demonstrates deficiencies in these methods. The potential role of mineralogy and other material characterisation methods is reviewed in detail, and a number of possible mineral processing strategies to mitigate drainage potential are considered. A more comprehensive block model would assist in the selection of such strategies in particular cases.

The paper closes by suggesting the research topics needed to achieve success, and development of a research project to address these is underway. A multi-disciplinary approach is essential if this ambitious but rewarding vision is to be realised.

## Introduction and Background

A radical idea is taking root in the world's mineral industry - the notion that if geologists, mining engineers and metallurgists can get together to plan and operate the mine holistically, then a much better result can be obtained than if they work in silos, as has historically been the case. The whole is indeed greater than the sum of its parts, and the benefits can be found across all the measures of sustainability - the value of the project (in terms of NPV), profitability, and perhaps even environmental impact. The idea already has a name – *Geometallurgy*.

Like many good ideas, of course, it is not new. Some operations have sought such synergies between the technical disciplines to achieve a better outcome, if informally. The “mine-to-mill” approach, which has been around as a formal practice for over 10 years, seeks to achieve optimal

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<sup>1</sup> We are conscious of some differences in the literature in the use of the terms “Acid Rock Drainage” (ARD) and “Acid Mine Drainage” (AMD). We have used ARD throughout the paper, which should be taken to mean any deleterious acid generation from mined rock, including waste dumps, stockpiles and tailings.

blasting fragmentation in the mine to maximise the throughput of the comminution processes in the concentrator. This process has become quite sophisticated, with simulation software, novel instrumentation, and new blasting practices contributing to an optimised value chain. However the hard-learned lessons of mine-to-mill are important:

1. It needs commitment and support from decision-makers in the company (a mine site General Manager for example), including appropriate KPIs to modify behaviour.
2. It requires a coherent methodology including robust tools to facilitate measurement and implementation (software and hardware).

These ideas came together about three years ago in the development of one of Australia's most important mineral industry research projects – *GEM<sup>III</sup>*, or *Geometallurgical Mine Mapping and Modelling* (AMIRA Project P843). Its purpose is to develop the tools and methodology needed to incorporate mineral processing attributes in the block model of the mine. This will allow “processability” to be included in the financial analysis and thus permit a more comprehensive optimisation of the mine plan and production scheduling, including modified processing strategies. *GEM<sup>III</sup>* is now about half-way through a 4-year initial programme, and is strongly funded by the international mineral industry and the Australian Research Council to the tune of \$8.5m. It is a collaboration between the University of Tasmania's ARC Centre of Excellence in Ore Deposits (CODES), and the University of Queensland's Julius Kruttschnitt Mineral Research Centre (JKMRC) and WH Bryan Mining and Geology Research Centre.

It is not a great leap of imagination to add environmental attributes to the mix. Indeed, as we show in this paper, this is not an original idea either, with some operations already incorporating ARD potential and other environmental attributes into mine plans. However this tends to be the exception rather than the rule, because the methods of assessing environmental attributes for this purpose are primitive and often non-quantitative. Even the measurement of ARD potential, the subject of much research and practice over many years, has problems as an attribute for mine planning, as others have pointed out and as we discuss further below.

Dowd (2005) makes a strong business case for the proactive prevention of acid drainage. The purpose of this paper is to suggest that this can be facilitated by incorporating acid generation potential more confidently into mine planning, if ways can be found of reliably quantifying the potential in a form which standard mine planning procedures require. This includes the development of processing strategies to limit acid potential and the release of deleterious minor elements. Reliable prediction is the key, which will require novel methods of material characterisation. Success in such an approach would allow a better valuation of the project, and a planning tool that would permit the mine to be operated to minimise environmental impact (including the requirements of mine closure) rather than relying on subsequent remediation. The central theme of this approach is therefore prevention rather than cure.

### **The Mine Planning Context**

Nearly all mines routinely manage the production process using proprietary mine planning software. This permits the ore deposit to be delineated according to geological principles. The best estimates of the grade of delineated blocks are obtained using geostatistical methods, and the mine is then planned and production scheduled to meet financial criteria such as project NPV. The methods are used both for assessing new projects and for managing current operations. At present the dominant attribute of the orebody used in planning and optimisation is the grade of the valuable component(s). Other attributes such as plant recovery are also sometimes used, and the menagerie of attributes is increasing, aided and abetted by the *GEM<sup>III</sup>* research project mentioned earlier. The

more comprehensive and realistic the description of the economic elements of the project, the more reliable and effective will be the evaluation of a new project or the planning of production.

One aspect which clearly impacts on project viability both in the short and long term is the disposal of waste, either coarse rock or concentrator tailings. This generally (but not always) has negative impacts on NPV related to loss of value, cost of disposal (including control of aspects such as ARD or other mobile deleterious elements), and ultimately cost of rehabilitation. Incorporation of this aspect into mine planning would seem to be a desirable enhancement of the planning methodology. However two issues first need to be resolved:

- Appropriate characterisation of the material that will report as waste, using quantitative criteria.
- Inclusion of such data into geological block models and mine optimisation and scheduling, i.e. into software, in a way which is mathematically robust.

In most jurisdictions mining companies are now required to plan for environmentally acceptable waste disposal to meet local and national regulations both for on-going waste disposal (including the management of any ARD), and for rehabilitation and ultimate closure. The larger companies have well established quality assurance standards of their own to ensure that the correct procedures are followed in the various jurisdictions in which they operate. Rio Tinto for example has an HSE audit standard for ARD prediction and control (Kelley, 2005). Once the production schedule is known for a given operation, blasting of overburden and ore can be conducted selectively, for example to generate coarse waste dumps that minimise acid generation (Tran et al, 2003). However in most of these cases, the planning relates to off-line prediction of waste properties and planning for the disposal of waste. It is not generally done as part of the routine mine planning using the geostatistical block models of the orebody.

Dobos (2005) however advises that a number of gold mines and at least one coal mine do incorporate acid potential attributes into block models for mine planning. Also, a few examples have been published. Bennett et al (1997) discuss the incorporation of ARD potential from waste into the mine plan. Several classes of material are identified, depending on the degree of projected acid generating potential. The block model is used for long term decisions leading to the estimation of the disposal costs of a given block of waste, and thus how it should be handled. Downing and Giroux (see website reference) advocate calculating a waste material estimate in conjunction with the resource estimate because of the importance for mine waste disposal. They list the useful ARD properties required to produce a meaningful block model from predicted acid generation characteristics. In their Windy Craggy case study (Downing and Giroux, 1993) calcium and sulfur were estimated by different geostatistical procedures (kriging and inverse squared method respectively).

Newcrest's Cadia mine reported using a waste block modelling approach to identify potential acid generating material within the deposit (DEH, 1997). Based on early identification and classification of the waste, a mine waste schedule was formulated to facilitate selective placement of waste rock within the waste stockpile and so minimise potential acid drainage. Several properties were used to select samples from the core log database for static testing of acid/base potential, from which waste types could be classified and incorporated into the block model. This was then used to predict how much and when potential acid drainage material will be produced during mining, and to selectively place the material in the waste dump.

The proprietary mine design packages can include any suitable attribute to develop the block model and so optimise design and scheduling to financial criteria. For example, the Whittle software (now part of Gemcom) can include cost related to acid-generating waste either as a rock-type mining cost or a rock-type rehabilitation cost, which can vary with acid 'grade' (Whittle, 2005). The result is a

disincentive associated with mining acid-generating material. Also if the cost of acid neutralisation is known, the resulting ‘benefit’ can also be incorporated, resulting in a corresponding incentive to mine acid-neutralising material (e.g. alkaline rocks, see Jenson and Barton, 2000). The Gemcom mine design software can in principle incorporate acid-generation potential ‘grade’ as it would any other element, which can then be geostatistically estimated in a mining block structure (Batista, 2005). The Datamine software has similar capabilities (Beaton, 2008).

It seems clear, then, that there is no technical impediment to introducing waste characteristics (particularly acid generating potential) into the block model for mine planning. However the methodology is not widely used and there are therefore some issues which are not resolved. These include:

- The appropriate measures of sulfide content and acid-generation potential for use in the block model, and the associated physico-chemical tests.
- The appropriate geostatistical procedures for estimating the ‘grade’ of these attributes in mining blocks. The statistical properties of the new attributes are not known (e.g. they may not be “additive”) and it may be that refined mathematical procedures will be necessary.
- The uncertainties in the resulting estimates of costs and project value.

Particular testing issues include the non-standardisation of testing for ARD potential (discussed further below), the wide range of standards and procedures adopted in different jurisdictions, and the development of effective predictive kinetic tests under the physical, chemical, environmental and climatic conditions that will actually prevail on site. The key issue for the present objective is that it is not known which waste characterisation methods are the most appropriate in the mine planning context.

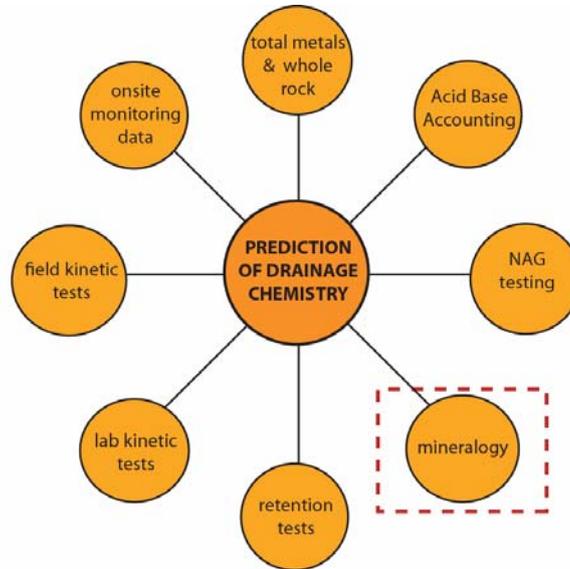
It is likely that small-scale, cheap procedures will be preferred to meet the needs of block modelling and geostatistical estimation which require many spatially distributed estimates. If drill core is to be assessed, then only very small amounts of material will be available for testing, and the methods used will have to take this into account. (The GEM<sup>III</sup> project mentioned earlier is specifically developing small-scale testing protocols to reflect processing attributes, and the analogy with ARD testing is exact.) In some cases the choice will be clear, in others less so. Research is required to evaluate a range of methods through their application in actual mine planning and optimisation case studies using mine planning software.

Once suitable tests are adopted or devised, they have to be accommodated in the block model. Some thought has been given to this problem but it is not fully resolved. Downing and Giroux’s work (1993) has already been mentioned. Dobos (2000b) has drawn attention to issues related to geologically uncontrolled sampling for ARD prediction, and Modis and Komnitsas (2007) have also considered the issue of sampling density. The statistical uncertainties in the results will also contribute to uncertainty in the final geostatistical estimates, and Rossi (2007) shows how this uncertainty can be accommodated using conditional simulation. However, more work is needed to fully understand the geostatistical properties of these new attributes and how best to accommodate them in the block model. In addition, the NPV model of project value which has stood the mining industry in good stead for many decades is insensitive to costs incurred late in the project (e.g. remediation and closure) and it may be that a refined model is needed to properly reflect the value of the full environmental impact of the operation throughout the mine life.

## The Problem of a Suitable Test for ARD

### The Status Quo

Current international standard practice has evolved into the “wheel” approach (Fig.1), which requires that all tests be conducted and compared. If a discrepancy between one or more test is identified, then additional work must be undertaken to explain and resolve this (Morin and Hutt, 1998).



**Figure 1 - The ‘Wheel’ approach of Morin and Hutt (1998) for the prediction of drainage chemistry and the likelihood of ARD (the dotted line shows an area that needs attention)**

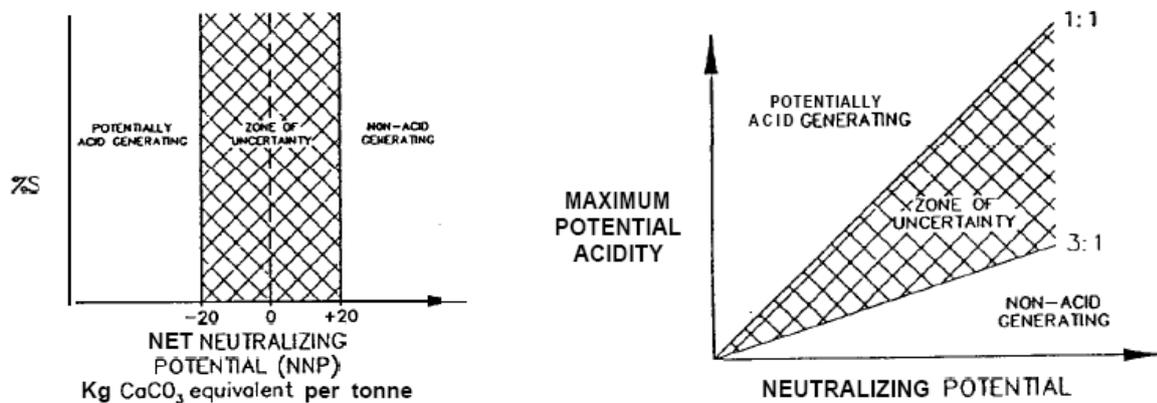
Whilst Morin and Hutt identify mineralogy as a part of the wheel approach, no advice is given as to what this actually entails and the opportunities which this presents are discussed further below. As this paper is focused on static tests, there will be only limited discussion of retention tests, laboratory and field kinetic tests and onsite monitoring data.

A typical predictive investigation could be viewed as starting at the top of the wheel and progressing clockwise, with geochemical assay data used to calculate total sulfur values (to deduce the maximum potential acidity or MPA). These values can be interpreted alongside data produced from wet-chemical acid base accounting (ABA) static test procedures which are used to obtain values for the acid neutralisation capacity (ANC) and also in some procedures refined MPA values. Several different static methodologies exist, including the Sobek test (Sobek et al., 1978), the Modified ABA (Sobek) method developed by Coastech Research Inc.(1989), the B.C. Research Initial method (developed in the late 1970s), the Lapakko Method (Lapakko, 1994), and the Sobek-siderite correction method (Skousen et al.,1997). Whilst each test varies slightly in terms of the chemical and physical parameters used, some critical generalizations can be made about them. These include the over-aggressive nature of the tests, inappropriately replicating a ‘natural’ environment, the absence of determining lag-times for acid generation (i.e. no rate component to the tests), incorrect estimations of MPA and/or ANC, and incorrect results produced as a result of human error (as the majority of tests involve wet-chemistry procedures). Dobos (2000a) summarised the errors associated with acid base accounting in a review of sulfide oxidation and acid mine drainage management in Australia, and identified several of the key problems with these tests.

There are additional problems concerned with protocol variables such as the particle size used (is it fully homogenized, and if so is this really representative of the geological strata?), the digestion

variables (i.e. the origin of acid used, the exact amount and the grade), temperature, the back-titration end-point (i.e. what represents a ‘real’ environment?) and understanding the role of bacteria. The major error incurred with static testing is the assumption that all acid-producing and acid-consuming minerals present will react completely, an assumption which ignores petrophysical properties such as mineral particle size, morphology, and presence or absence of veins/fractures (White et al., 1999).

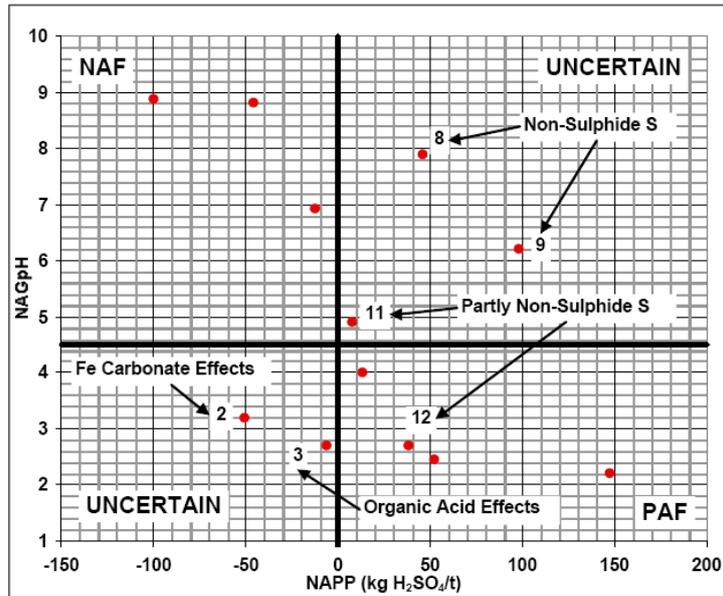
Despite these potential uncertainties, both ANC and MPA values are used to calculate either the Net Acid Producing Potential (NAPP) as is typically the case in Australia, the Net Neutralising Potential (NNP) as used in North America, and/or the Neutralising Potential Ratio (NPR) all of which are described in more detail in Skousen et al. (1997), White et al. (1999) and Bezaazoua et al. (2004). Samples are classified as acid producing or neutralising and can be graphically plotted; however an area of uncertainty exists as shown in Fig.2. Typically, it is recommended that these uncertain areas are subjected to kinetic testing for characterisation. Kinetic tests are considerably more expensive and last for months or even years (White et al., 1999). Instead of turning directly to kinetic testing to classify uncertain samples, it is possible to test the accuracy of the NAPP test results by comparison with Net Acid Generation (NAG) test results as developed by Miller et al. (1997). The NAG test is a direct measure of the ability of the sample to produce acid through sulfide oxidation and also provides an indication of the reactivity of the sulfides and the available ANC. A description of NAG tests can be found in Miller et al. (1997); White et al. (1999) and Lei and Watkins (2005). Miller et al. (1997) described the use of NAG tests in conjunction with ABA methods to classify samples as providing a better definition of acid forming potential and reduce the risks of misclassifying non acid forming (NAF) materials as potentially acid forming (PAF) which is termed a ‘Type 1’ error, and vice versa which is termed a ‘Type 2’ error (following the conventions of statistical hypothesis testing).



**Figure 2 - Uncertain areas (Robertson and Broughton)**

Stewart et al., (2006) undertook both NAPP and NAG tests to classify twelve lithologically diverse samples (ranging from carbonaceous mudstone to basalt to tailings) and presented the results graphically on an ARD classification plot. The motive for this study was to show the benefit of classifying samples using two different static test procedures and also to identify potential errors with specific tests in determining ANC and MPA estimates and determine which require further investigation. The calculated results are shown in an ARD geochemical plot in Fig.3.

The results categorised three samples as NAF, and four as PAF. Samples plotting in these domains thus have consistent NAPP and NAGpH results and have been classified with a greater degree of confidence than if one test procedure had been used alone. However, despite using both test procedures uncertainty remains with five samples classified as Uncertain (UC), thus returning conflicting NAPP and NAGpH results.



**Figure 3 - ARD geochemical plot for the case study sample set (Stewart et al., 2006).**

Stewart et al. (2006) suggested that where uncertainty exists, samples should be subjected to more sophisticated short duration tests such as sequential NAG, modified organic carbon NAG, modified ANC methods (to account for siderite), Acid Buffering Carbonate Curve (ABCC) testing (additionally the Net Carbonate Value (NCV) test could also be used). However, it is anticipated that whilst these tests may return more accurate results, several potential problems as outlined by Dobos (2000a) would still apply. We therefore suggest that more attention be given to a comprehensive mineralogical assessment (see Fig.1) as opposed to immediately turning to field- and lab-kinetic tests to define uncertain or marginal samples. The idea is not to supersede either static or kinetic tests, but rather to serve as a complimentary set of protocols, which can return likelihood of ARD generation data faster than kinetic tests based on the actual mineralogy present rather than composited samples which may not always be wholly representative. Many powerful mineralogical and textural techniques now exist which can be exploited in this application. The GEM<sup>III</sup> project is developing such techniques for processing attributes and these may also be applicable to some environmental attributes.

### A Case Study

The following example demonstrates the shortcomings of conventional static ARD tests for a decisive assessment of potential environmental hazards from mine wastes in a real case. The study investigated potential acid drainage and release of soluble metals, arsenic and cyanide from a heap leach stockpile. The stockpile also partially contains mill rejects and other forms of waste which can make geochemical characterisation difficult.

The mine site is located in a semi-arid, sub-tropical climate of Australia with 660 mm of annual precipitation falling in high density storms between November and March. Mining operation commenced with heap leaching of oxide ore and continued with carbon in pulp processing of primary un-oxidised ore from a large open cut. Dominant sulfides were pyrite, chalcopyrite, galena and sphalerite with main gangue minerals including chlorite, carbonates, mica and quartz.

The spent heap leach materials have been used in the cover systems for the tailings storage areas, and other areas including parts of the waste rock dumps, ROM stockpile, the plant area, and the

magazine area. The materials have been also used in the structure of runoff and seepage containment dams. The heap leach stockpiles area has been partly covered with topsoil and seeded.

Heap leach materials are usually subject to high flow rates, providing greater and more extensive rinsing of particle surfaces than occurs in typical waste rock dumps. The quality of water draining from the heap will depend on the geochemistry of the ore which had been leached, the amount of evaporative concentration that has occurred and the amount and type of chemicals that had been added to the process solution during leaching (Miller et al., 1999). Apart from reviewing on-site water quality monitoring data, a proper characterisation of the heap leach material for the prediction and control of drainage chemistry is necessary. Such a study should include (Morin and Hutt, 1999): acid-base accounting, NAG testing, mineralogy, kinetic tests (field and laboratory), assessment of the retention of cyanide and metals, and total metals and whole rock analysis (Fig.1).

Compared to trace element compositions for average felsic and intermediate rocks (e.g. Levinson, 1974), concentrations are all enriched in the samples analysed. Samples also show wide range of concentrations for Mn, Co, Fe, Ni, Zn, Ti and cyanide. There are apparent higher concentrations of Ni and Cu and to a less extent Cr, Co, V, Mg and Ti in the samples collected from the pad area that may suggest the accumulation of less mobile elements at depth of the stockpile and above the liner.

The laboratory results also show that paste pH values of near neutral or alkaline prevail in the samples (Table 1). Total sulfur contents for samples analysed are in the range of 0.02-2.08 mg/kg and show a positive correlation with the sulfide S. However, the data plot above the 1:1 ratio line for total S vs. sulfide S, which indicates the importance of other forms of sulfur. Samples were analysed for soluble sulfate and values between 210-550 mg/kg of soluble sulfate were detected. That means firstly that using total sulfur in the calculation of potential acidity would have been an overestimation of potential acidity, and secondly underlines the importance of secondary sulfate salts in distribution of acidity in the leach heap. The X-ray diffraction results for secondary minerals/salts precipitating at the surface of the heap leach material as white precipitates are mainly alunite group with some clays and green alunite, and minor copper zinc, manganese oxides, Cuprite and spinel group minerals.

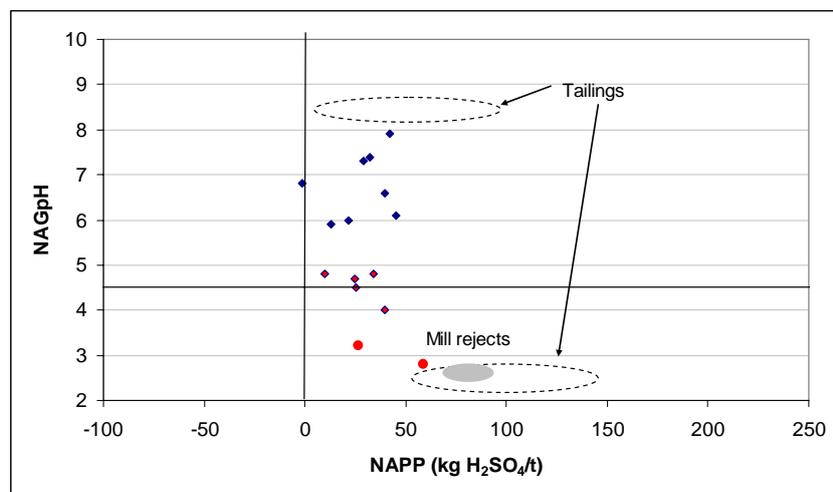
**Table 1 - Summary of geochemical test results for the heap leach materials (16 samples)**

Paste pH	Total S (% S)	Sulfide S (%S)	Soluble sulfate (mg/kg)	Fizz Rating	ANC (Kg H <sub>2</sub> SO <sub>4</sub> )	NAPP (Kg H <sub>2</sub> SO <sub>4</sub> /t)	NAG (Kg H <sub>2</sub> SO <sub>4</sub> /t)	Final pH
5.2-8.9	0.02-2.08	<0.01-1.5	210-5550	0	1.9-10.3	-1.5-58.8	<0.1-14.9	2.8-8.4

Although sulfide S concentrations in the samples are relatively low (0.32-1.5 mg/kg) compared to other waste materials on site, for example the mill rejects (2.06-3.83 mg/kg), they still show the potential to produce acid. Ore microscopy revealed well preserved pyrite in a number of rock fragments, although pyrite crystals are generally leached, deformed and oxidized through the heap leaching process and subsequent weathering and oxidation in the heap. The materials tested consist of either intrusive rocks with granular texture including quartz, feldspars and sericite/clay minerals or volcanoclastic (breccia) rocks with plagioclase and quartz as dominant mineral fragments in a less crystallised groundmass. The presence of apatite, although not identified in the thin sections, is suggested by high concentrations of phosphorous in all samples. Both groups of rocks have little neutralizing capacity. The neutralization potential of feldspars, for example, can be up to 50 times less than calcite, depending on the type of feldspar (Jambor et al, 2000; Plumlee, 1999).

The acid production potential of the materials tested was assessed by comparing with the most common interpretations of NAPP and NAG test results.

- The relatively high remnant sulfides in the heap and low NP/AP ratios suggest that the samples are “likely” to produce acid (Soregaroli and Lawrence, 1997).
- Most materials (14 samples) have NAPP values greater than 20 and NP/AP ratios <1, which indicate they are “potentially acid generating” (Hutchinson and Ellison, 1992).
- Since all samples have negative NNP and <1 NPR they are “eventually acidic” (Morin and Hutt, 1997).
- The pH values do not change with NNP, which means the samples are at an early stage of acid generation. So, although the results of the static tests suggest that the samples will eventually produce acid, this has to be verified with kinetic tests. Static tests use powdered or crushed samples for analysis which artificially increase grain size and exposure more mineral grains to reaction. But over time, sulfide minerals may be entirely liberated from the rock matrix, occur interstitial to other minerals (partially liberated), or occur as inclusions within other minerals. Lottermoser (2003) explains other reasons for the uncertainties associated with static tests.
- The NAG test results suggest that only 4 samples are definitely acid producing and the rest of the samples are uncertain (Miller, 1998).
- When combined with NAPP results (Figure 4 – as utilised by Stewart et al, 2006; see Fig.3), 2 samples have NAG pH <4.5 and NAG value >5 (t H<sub>2</sub>SO<sub>4</sub>/1000 t) and positive NAPP, and hence are “potentially acid forming with high capacity”. Four samples have NAG pH values near 4.5, NAG values >5 and positive NAPP, so are “potentially acid forming with low capacity”. The rest of the samples are uncertain (Lottermoser, 2003). In any case, the NAG and NAPP values for the samples tested are much lower than those reported for mill rejects.



**Figure 4 - Plot of NAGpH versus NAPP**

It shows that 4 samples are potentially acid forming, three samples are near the 4.5 NAGpH and the rest are uncertain. Circles show plot area for tails and mill rejects

So while the NAG results suggested that only four samples were definitely acid producing and the rest of the samples were uncertain, the NAPP test results suggested that almost all samples were potentially acid producing. In such cases, detailed mineralogical assessment is crucial to the decision making process. With the advent and development of more sophisticated mineralogical and microanalytical techniques there is good opportunity for petrographic examination beyond the simple identification of sulfides (above example) and possibly generation of environmental mineralogical models, calibrated for similar paragenesis and settings, based on textural/morphological classifications and other attributes.

## The Role of Mineralogy in ARD Prediction

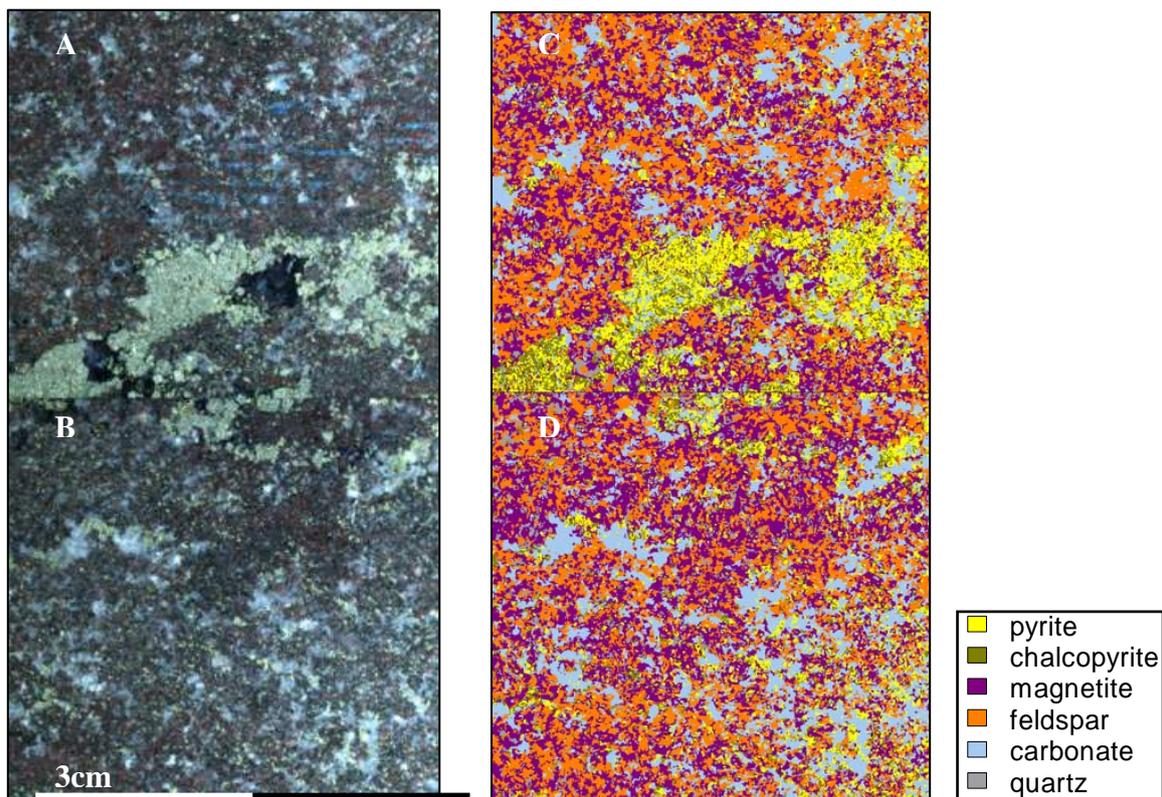
Jambor and Blowes (1998) described mineralogical studies as falling within any four environmental facets of prediction, prevention, control and remediation. The focus of this paper (and our future research) is concerned with prediction. We believe that a clear quantitative understanding of the mineralogy is needed to accurately predict the potential for ARD generation. In many instances, particularly where ARD systems are studied in order to assess or predict water quality, the mineralogy is largely ignored. The reasoning for this is that detailed environmental mineralogy is regarded by industry as time consuming and expensive, and additionally requires the employment of a skilled environmental mineralogist (Downing and Madeisky, 1997; Shaw and Mills, 1998).

In more recent years, it has been acknowledged that mineralogical characterisation is useful and even necessary, with several different procedures and guidelines. Blowes and Jambor (1990) undertook an ARD generating potential investigation on samples taken from the Waite-Amulet tailings facility in Canada, from which the Sulfide Alteration Index (SAI) was developed. This was used to interpret the degree of weathering of the dominant iron sulfide phases, and thus deduce the remaining acid generating potential. Lawrence and Scheske (1997) calculated the effective NP from mineralogical composition and determining the relative reactivities of component minerals from analytical values using a CIPW normative procedure. A limitation of this type of interpretation is that CIPW calculations were developed specifically for unaltered magmas, and thus cannot be applied to sedimentary, metamorphic or altered igneous rocks. Downing and Madeisky (1997) undertook a similar approach and devised a method of predicting ARD buffering capacity based on bulk chemistry and modal mineralogy. Paktunc (1999) developed mineralogical constraint diagrams relating NP determinations to Ca, Mg and CO<sub>2</sub> concentrations to serve as supplementary guides to conventional static tests in identifying possible NP contributions from non-carbonate minerals and checking the quality of the chemical testing results. More recently, Jambor et al. (2007) compared NP values for 19 samples determined by the Sobek method with computed values determined by the quantitative mineralogy of the samples. Most of the computed NP values of the rocks were lower than the measured values, but a close relationship was evident.

Whilst these papers represent positive directions in integrating mineralogy into ARD predictions, there still remains an absence of routine detailed work and/or interpretation (Shaw and Mills, 1998). These papers also do not focus too much attention on examining the mineralogical textures, with perhaps the nearest considerations given by Blowes and Jambor (1990) with the development of the SAI and later by Jambor (2003) who described in detail the paragenesis and of primary and secondary minerals formed in ARD settings. It is crucial to understand the mineralogical form and textural relationships as these provide valuable information regarding the sources and likely evolution of ARD. Furthermore, a scaled approach should be developed with consideration given on a meso- and microscale. Mesoscale environmental mineralogical characterisation would typically involve undertaking routine drill core logging but with a focus on key environmental parameters. In theory these would include the classification and quantification of a variety of the dominant sulfide mineral phases and form (e.g. coarse-finely disseminated, clotted); location of acid generating sulfide phases (e.g. within mafic or felsic minerals or within layered units); dominant carbonate mineral phases and spatial location relative to acid generating sulfides; alteration phases (MPA or ANC contributing?); textures of acid producing sulfides and carbonates both independently and relative to each other (e.g. are sulfide phases disseminated within a carbonate-rich cement?); presence of fractures (orientation, cross-cutting which lithologies? length? fracture infilled? Does the infill have a specific texture?).

Semi-quantitative MPA/ANC estimates could be made through such environmental evaluation, or *e-logging*. E-logging would provide a large amount of environmentally focused mineralogical data

surplus to that gathered by the site geologists, and a crude estimate of likelihood of ARD generation potential could be made as a first step to understanding the environmental geochemistry of an unmined economic ore body. Exploiting new technologies appearing on mine sites such as high-resolution imaging tools installed on automated loggers, low-cost drill core imaging can be rapidly undertaken which suggests that e-logging would not necessarily have to be undertaken on site or by skilled geologists thus saving time and money. It is important to realize the potential of such automated loggers; they are not just used to collect core photographs but also are used to acquire RGB images which are subsequently interpreted mineralogically using software such as *DEFINIENS* with classified images produced as shown in Fig.5. This approach has been developed for geometallurgical classification for various world-class ore bodies at CODES, and could easily be adapted for e-logging purposes on waste rock samples to aid waste block classification and waste dump planning.



**Figure 5.** (a) and (b) Geotek Multi Sensor Core Logger images of drill core tiles (9cm<sup>2</sup>) taken from an iron-oxide copper gold deposit. (c) Classified mineral map of the drill core image (a) showing pyrite dominance (relative to other acid generating phases) in the form of clots which are not directly spatially associated with carbonate phases. (d) Classified mineral map of the drill core image (b) where pyrite is disseminated throughout but is in close spatial association with carbonate mineral phases. Based on this, a crude interpretation would be that sample (a) would be more acid producing than sample (b); however the nature of the feldspar present (AP or NP?) and indeed the type of carbonate present would need to be further determined.

(Images courtesy of Professor S. Walters, CODES, UTas).

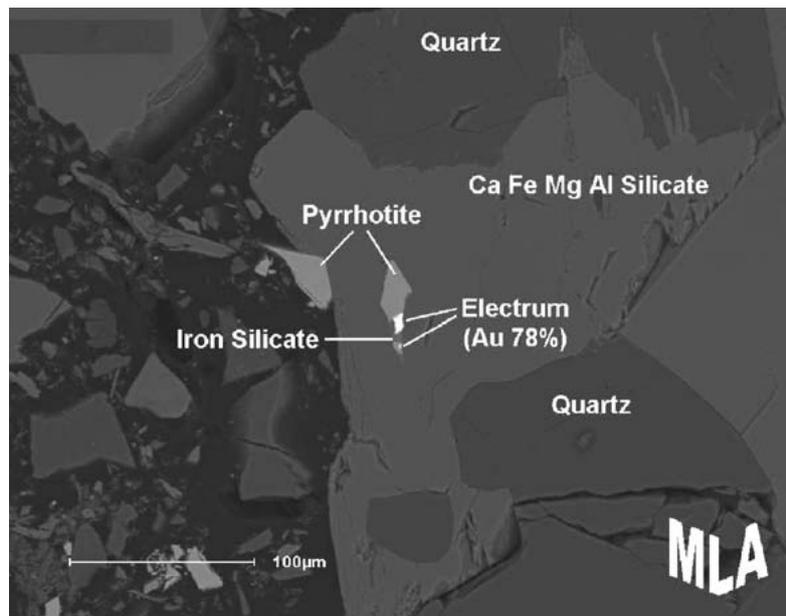
Whilst e-logging performed visually and also using automated systems with classified images produced such as that in Fig.5, vital information is missing concerning the types of carbonate and feldspar minerals present. This is significant as carbonate minerals obviously have differing ANC values, as do feldspar minerals as detailed in Plumlee (1999). On a mesoscale, distinguishing between carbonate and feldspar phases can be undertaken through basic staining procedures as detailed by Hitzman (1999) and Fox (2007), or indeed can be undertaken more sophisticatedly using CSIRO's range of HyLogging<sup>TM</sup> tools as described by Holliday and Cooke (2007) in a review

of the exploration methods applied to characterisation porphyry Cu-Au deposits. These HyLogging™ tools are based on the principles of reflectance spectroscopy and will readily identify mineral assemblages common to many geological units and hydrothermal alteration units. Semi-quantitative mineralogy and associated mineralogical parameters such as intensity of alteration, crystallinity and chemistry can also be extracted from the HyLogging™ data. Core is prepared and scanned, with semi-quantitative data efficiently collected (~100 core-trays/day). This data is then interpreted using software such as *The Spectral Geologist*. Using technology such as this in conjunction with staining procedures, a low-cost repository of detailed NP mineralogical data could be relatively rapidly collected.

Microscale characterisation is currently undertaken through petrological examination of samples using transmitted and reflected light microscopy, and also by various X-ray diffraction (XRD) techniques. By undertaking such routine or sophisticated techniques, reaction products of sulfide oxidation (e.g. rimming of grains) are readily observed as are many other characteristics of mineral grains not readily seen by other investigative techniques.

The objectives of geoenvironmental microscopic characterisation are straightforward, and would involve the use of basic optical microscopy with consideration given to a range of parameters including sulfide morphology, mineral inclusions, microtextures, presence/absence of coatings-microfilms, resistance to oxidation, presence/absence of cements, fixation of metals, trace element composition of sulfide phases, alteration and clay mineralogy, and mineral-microbe interactions involved in weathering of minerals. Micro-scale physical parameters (i.e. presence of fractures) should also be identified and quantified. The use of sophisticated analytical tools typically applied to ore-characterisation have been utilized in environmental investigations and include the use of SEM (Klich et al., 2002) EPMA (Robinson et al., 1998), LA-ICP-MS (Al et al., 2000; Öhlander et al., 2007) and micro-PIXE (Cambri and Campbell, 1998). The use of these sophisticated techniques is generally confined to interpreting sulfide minerals where compositional abnormalities affect ARD testwork interpretation (Shaw and Mills, 1998), and furthermore are expensive to undertake. Thus only a relatively small number of samples would be routinely characterised in this manner.

An opportunity for developing a rapid, low-cost sophisticated analytical approach exists through the use of JKTech's Mineral Liberation Analyser (MLA) Scanning Electron Microscope (SEM) system, which is being used in the GEM<sup>III</sup> project. The MLA represents a unique method of combining BSE image analysis and X-ray mineral identification to provide automated qualitative mineral liberation characterisation (Fandrich et al., 2006). There are eight basic MLA measurement modes, which vary from a purely BSE-based technique to an almost exclusively X-ray analysis point counting technique (XMOD). The current levels of automation extend from de-agglomeration functions to the ability to probe unidentifiable phases (Latti-method) and to recognise mixed spectra (standard trigger). Currently, SPL (Sparse Phase Liberation analysis) and RPS (Rare Phase Search) modes are performed on tailings. SPL functions have been used to efficiently measure tailings and low-grade feed ores (e.g. platinum group mineral ores) where the mineral associations of the phase of interest are of importance. Typically, RPS is used on tailings to accurately locate very fine (i.e. sub-micron) components such as Au in tailings as shown in Fig.6. Images such as this could be used to confidently identify mineral phases and environmental microscale textures present, as well as providing valuable sulfide liberation data (Shaw and Mills, 1998), thus by spatially speciating acid generating phases crude assumptions regarding the evolution of ARD could start to be formulated, without having to wait for the construction and evolution of kinetic tests. Given the ever increasing presence of SEM systems on mine sites the development of this powerful analytical tool for ARD predictive mineralogical purposes is a desirable objective.



**Figure 6** - Au located in RPS mode in a tailings sample (Fandrich et al., 2006). Pyrrhotite is identified both within and external to the major Ca Fe Mg Al silicate phase seen. Interpreting MLA-SEM data already assimilated in this manner (typically for geometallurgical purposes), in terms of identifying and classifying the environmental textures, will add much in producing an accurate ARD generating potential prediction, as surface areas contributing to MPA and ANC reactions could be more accurately predicted.

The geoenvironmental classification of textures undertaken through newly developed methodologies represents a new direction that predictive mineralogy work in ARD assessments could take. Further value can be added through the use of non-destructive no-preparation  $\mu$ -XRF technology to produce nanoscale deleterious element data. Micro-XRF technology can produce high resolution low-cost element maps down to a  $10\mu\text{m}$  scale as well as performing multiple quantitative spot analyses returning concentrations of deleterious elements present with relative ease (Croudace et al., 2006). Thin sections and polished blocks can be subject to analysis in these machines, and do not need to be crushed and powdered as is the case with traditional XRF. The output element maps spatially speciate multiple elements (as selected by the operator), and these images can be interpreted in conjunction with reflected/transmitted light images to understand the element-mineral associations. Such deleterious elemental data is relatively quick to obtain and should be used for 'deleterious-element auditing' though would not be anticipated to replace traditionally used wet-chemical procedures such as sequential extraction procedures and TCLP/SPLP tests. The outputs from the  $\mu$ -XRF should thus be viewed as a complementary tool, and if used together with routine sequential extraction procedures, more efficient methodologies for speciating and quantifying deleterious elements could be produced.

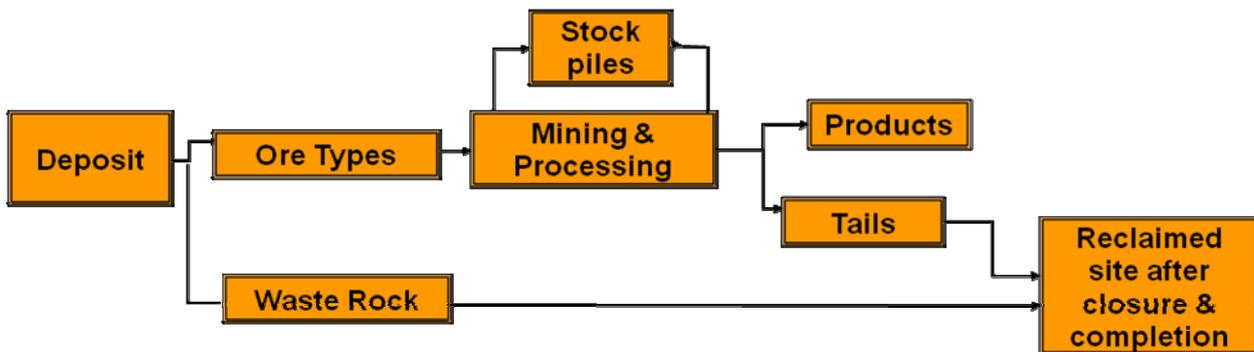
## Mineral Processing Strategies

### Sulfides

Much of the management of sulfidic wastes from mining operations has concentrated on remedial action once the waste is generated. This is also true of the associated research activities. It is self-evident that an alternative approach is to limit the generation of the waste in the first place, or to generate it in a more benign form. This conforms to the principles of 'cleaner production' (Van Berkel, 2002) which is increasingly espoused as an appropriate context in which to plan and manage mineral processing operations. The role of mineral processing in this respect has been well understood in principle for some time (Feasby and Tremblay, 1995), though the practice has lagged

the understanding. This part of the paper considers mineral processing strategies for limiting ARD potential.

Many common metals, and some precious metals, occur in nature as sulfides or associated with sulfides. Coal also is sometimes associated with sulfides, usually pyrite, and coal preparation is carried out to generate a clean coal product, with the waste, including associated sulfides, being rejected as tailings. In metalliferous operations, mineral processing is carried out on the mined ore in order to separate the valuable sulfides from the non-valuable components, which may comprise sulfides and/or non-sulfides, as shown in Fig.7.



**Figure 7 - Schematic of Mining Operation (does not include smelting or refining)**

When sulfides are processed there are two sources of sulfidic waste to consider:

- The unintentional loss of valuable sulfides (e.g. chalcopyrite in a copper operation).
- The intentional rejection of non-valuable sulfides (e.g. pyrite and pyrrhotite).

In the great majority of cases, the sulfides are concentrated by froth flotation, in which selectivity is achieved through chemical conditioning of the mineral surface. It is a prerequisite for flotation that the ore first be finely ground so as to liberate the mineral species in the rock from each other. This almost guarantees that any resulting sulfidic waste is in the optimum reactive state to generate acidic products as it is consigned to a dam or other impoundment (though this is not a problem with rock dumps and ARD).

These facts suggest five approaches to the minimisation of the negative impact of sulfidic wastes through alternative mineral processing practices:

1. Improvement of the recovery of valuable sulfides, which will reduce the tonnage of acid-generating material reporting to the waste product.
2. Improved grinding and classification efficiency, to avoid over-grinding of sulfides thus reducing acid-generating potential.
3. Pre-concentration at a coarse size (ie before grinding and flotation), so that some waste sulfides remain locked in coarse waste rock and therefore less mobile, such that reaction rates are greatly reduced.
4. The deliberate concentration and separate disposal of waste sulfides. Included in this option is the further processing of tailings to 'recover' the waste sulfides from primary tailings for separate treatment and/or disposal.
5. Novel treatment processes.

Interestingly the first three of these options (and possibly the fifth) also have benefits in the economic performance of the process as a whole, quite separately from the desirability of limiting the negative impact of waste sulfides. The first is obviously the constant objective of all process metallurgists, and the next two will contribute to a reduction in comminution energy, which is a major current objective of the mineral processing and associated research communities (comminution is a heavy user of electrical energy and is therefore a significant cost to the operation as well as contributing indirectly to greenhouse footprint through the generation of electrical power). Only Option 4 is likely to lead to additional cost with no immediate return in revenue or cost saving, unless the waste sulfide can be converted to a saleable product which is always problematic; the commonest product is of course industrial acid and this is generally in over-supply.

In general the focus of a mining operation is to maximise the recovery of the minerals containing the valuable metals in the most efficient and economical means possible within the constraints of the sales contract (not necessarily even the most effective). One of the practices that has arisen from this is the focus on throughput where, within normal operating constraints, concentrators have shown that the delivery of tonnes of metal in the concentrate is easier to maximise through increased throughput than through increased valuable mineral recovery. This means that in the case of sulfide flotation, an unnecessary amount of valuable sulfides can be sent to tailings where, along with other iron sulfides that are rejected as unwanted gangue, they become susceptible to acid drainage. This is exacerbated by the smelter operation being grade-driven and a higher recovery from the concentrate being achieved with higher mass recovery and thus lower grade and potentially more deleterious minerals attracting smelter penalties.

Cilliers (2006) has discussed this phenomenon in terms of ‘active and passive gangue’ demonstrating for several strategies producing lower sulfides in tails that the potential ARD legacy from the tailings can be reduced. However he showed that the difficulty in properly valuing alternative strategies arose from the shortcoming in the estimation of the cost of long term tailings management and noted that this was an area requiring urgent attention from plant operators, economists and environmentalists.

Several processing strategies are available to reduce the acid-generating impact of processed products, particularly tailings:

Improved recovery of sulfide values. This is the objective of all process metallurgists. There is much current research in this area, the scientific literature is correspondingly large, and operating practice diverse. In general, the target mineral recovery and grade of the concentrate is set on economic terms by the smelter contract. By increasing the recovery of sulfides to the concentrate further, the tonnage of acid generating material reporting to the tails is minimised. However the higher recovery of the target sulfide minerals is generally achieved by lowering the concentrate grade and is often accompanied by increased minor elements in concentrate with associated increased treatment charges and penalty payments (Cilliers, 2006). This makes it an unattractive option. However with a more holistic view of benefits and value, taking into account responsible stewardship, a different decision could be made. This needs better economic valuing of acid and metalliferous drainage and costing of the penalties to the smelter as well as potentially novel separation strategies, and the capture of the relevant information in the mine plan.

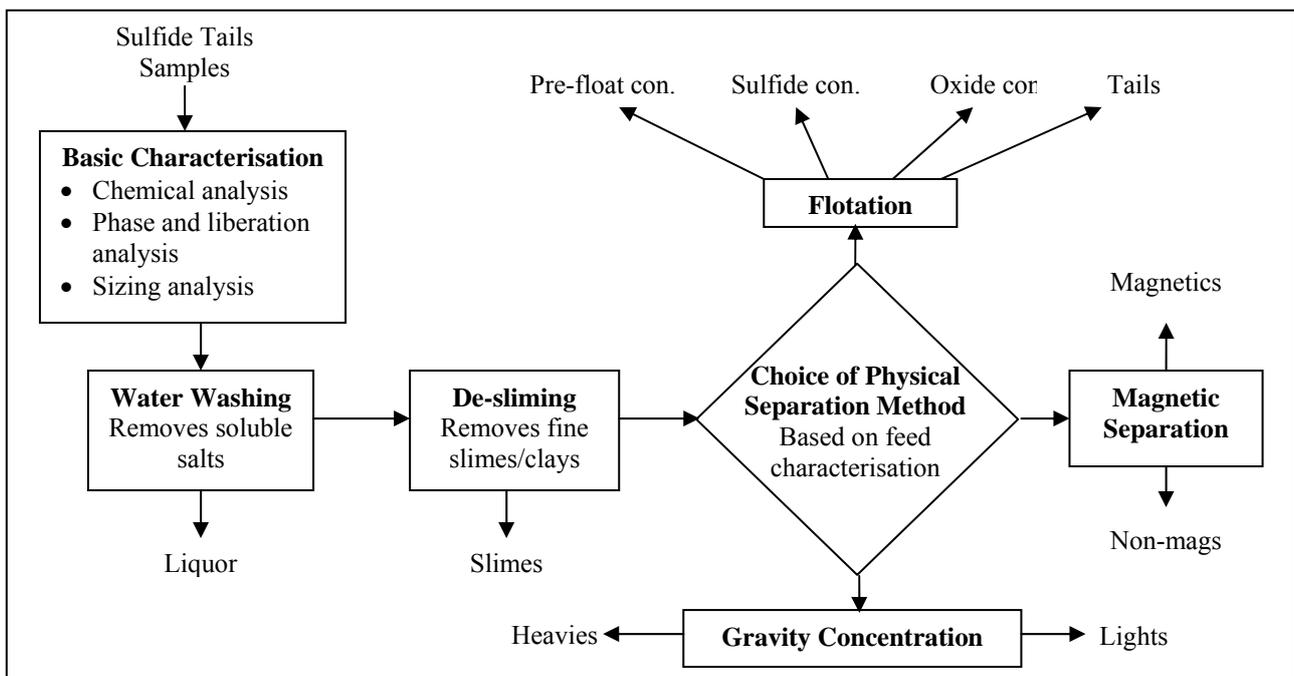
Although not specifically *reducing* the amount of sulfide reporting to tails, an important option to consider is the possibility of managing the production flotation process to ameliorate the conditions in the tailings dam (Dold and Fontboté, 2001). For example, the use of appropriate collectors may allow flotation to be carried out at higher pH; this has been achieved at Kennecott Copper. Minerals such as feldspars and clays in tails can also neutralise low pH water over time and it may

be possible to create flotation conditions that enhance this effect. Blending ore sources may also assist this approach.

Improved grinding and classification efficiency. Again this is the objective of every operating metallurgist, and it has some commonality with the preceding and following topics. However in current operations it usually means achieving a particle size range in flotation feed that maximises the recovery of valuable minerals. It is not usually thought of in terms of minimising ARD potential in the resulting tailings dam. In many cases the two objectives can be achieved by the same set of conditions, as the prevention of over-grinding will also probably reduce the loss of valuable sulfides to tailings and reduce the potential for ARD from those sulfides which end up in the dam. A well-known problem is the classification of minerals in grinding circuits using hydrocyclones, which separate on the basis of hydrodynamic properties such as size and density. This can lead to misplacement of fine heavies which leads to overgrinding. There are alternative technologies which can address this problem, for example the three-product cyclone which generates an intermediate product which can be separately processed (Obeng and Morrell, 2003).

Liberation and pre-concentration at a coarse size. This is an old idea but with many potential new angles. If low grade waste can be rejected at a coarse size, the amount of material to be ground and floated can be reduced, resulting in less fine ARD-generating tails. Coarse liberation can be controlled either by modified blasting practice or modified comminution equipment and flowsheets or both, and research is underway to achieve these. Coarse low grade waste can then be rejected by processes such as dense medium separation or ore sorting, thus reducing the volume of ore to be conventionally ground and concentrated

De-sulfidisation of tailings. The removal of sulfides from the tailing streams before disposal by various methods is an obvious strategy and has been discussed by several authors (Dobos and Lee, 2000; Bruckard et al., 2007). This approach requires that the streams be well chemically and mineralogically characterised to identify potentially suitable techniques. Techniques include gravity and flotation and magnetic separation. Figure 8 shows a systematic approach to assessing which processes are appropriate.



**Figure 8 - Schematic of the diagnostic separation technique developed and used for assessment of sulfide tailings (from Bruckard et al. 2007)**

For certain ores which do not require very fine grinding it may be possible to use high-G gravity separators to selectively recover the sulfides from tails, at much less cost than flotation (Lyman et al, 2000). Canadian practice has favoured the use of flotation to recover waste sulfides from tailings, and has succeeded in making benign soil as a by-product. OK Tedi and Freeport have also adopted this approach. Kolahdoozan and Yen (2002) describe experiments to depress pyrrhotite in flotation. Hydrocyclones have been used to remove fine pyrite from soils (Guerny et al), and cyclones used to prepare tailings for the building of dam walls have been known to preferentially concentrate sulfides in the underflow which locks them into the wall rather than in the dam itself. British Columbian guidelines (Price and Errington, 1998) include mineral processing strategies such as finer grinds or deposition procedures which create tailings with reduced pore size, increased moisture retention and reduced conductivity, or addition of a flotation circuit to remove iron sulfides, producing a large mass of benign rougher tailings and a smaller amount of sulfide-rich tailings.

Mine backfill. This is a method of disposing of tailings, including sulfidic wastes, underground (Dorracott and Grice, 2002), though site-specific work is generally required to assess the potential for acid generation and dispersal from the movement of groundwater through backfilled excavations. Also sulfides in backfill can sometimes lead to loss of strength due to sulfidisation of the added cement, though there are solutions to this problem.

Novel treatment processes. Radical approaches are being considered to meet the challenges of achieving significant mineral processing efficiencies in the future. It is worthwhile considering how these could also mitigate the generation and disposal of sulfide wastes. One approach is to move wholly or partly to dry processing (Napier-Munn and Morrison, 2003). This is being considered in the context of the scarcity and therefore cost of water for some mining operations. However dry operation would also allow dry disposal of sulfide wastes as cemented 'fill' (see below) which may prove beneficial environmentally. It might also permit the processing of the waste to a benign form.

#### Minor and Trace Deleterious Elements

The base metal industry mines and processes hundreds of million tonnes of ore per annum to produce saleable products and large tonnages of waste by-products such as tailings. These ores usually contain less than 1 wt per cent of toxic elements (arsenic, antimony, bismuth, cadmium, lead, mercury, selenium, tellurium etc), in various mineral departments which are subsequently treated with the other components in the ore during the production of concentrate. The departments of minor elements across the various unit operations of a process flow sheet do not normally receive the attention that the major elements receive. However, these minor elements can have a major influence on the quality of the products (both saleable and waste) as well as an economic and environmental impact (Jahanshahi et al., 2006). In addition to this during the mineral processing step these concentrations can increase dramatically (Broadhurst et al., 2006). The mobility and contaminant pathways of these elements are dependent on their initial department in the ore, together with the grain size, texture and association as well as the alteration and weathering of the ores being processed with contributions from the particular means of processing and its effectiveness. These elements, to varying extents, have a range of commercial uses and consequent values and the potential exists depending on their department and concentration to develop appropriate strategies for extraction potentially in the processing step or later hydrometallurgically.

Treatment options for various penalty elements are determined by the nature of their occurrence, their association with other elements and their distribution. In extreme cases high values in deposits can make deposits unviable. One approach is to characterise and domain the different ore types in the deposit and either not process those ores with deleterious minerals such as arsenic or blend them

to create a suitable feed grade (Schwartz, 1995). Another approach is to process these ores separately with an operating strategy to handle the deleterious minerals, by either depressing them or by recovering them to a separate stream for careful and safe disposal or further processing for an economic product.

This approach requires a knowledge of the deportment of the minor elements in the various mineral phases as well as the behaviour of them in the process and it is possible to separate them by manipulating operating conditions, ie enargite from chalcopyrite (Jahananshahi et al., 2006), or arsenopyrite from pyrite (O'Connor et al., 1991). At Kennecott Copper, the arsenic-bearing copper minerals enargite and tennantite report with the copper sulfides, whereas realgar and orpiment report with the molybdenite concentrate. At certain trigger concentrations the molybdenite concentrate is leached before dispatching (Adair, 2008).

Another example is the addressing of fluorine in the copper/gold concentrates produced by Ok Tedi Mining Limited which has provided a series of challenges to metallurgists since 1988. Although fluorine is distributed throughout the gangue minerals contained within Ok Tedi ores, its presence in talc and phlogopite (naturally floating fluorosilicates) has proven to be the predominate sources of fluorine in the final concentrate. Initial treatment for the fluorosilicates consisted of the use of a carboxy methyl cellulose and depression of these minerals. This was superseded in 1998 with the installation of a fluorine reverse flotation process for the removal of naturally floating fluorosilicates from the final concentrate when the fluorine content of the final concentrate exceeded smelter-defined trigger points (Lauder et al., 2003).

The drivers for change in processing can also come from specifications on concentrate grade (e.g. minimum trace elements), specifications on tails grade for disposal, or the potential to gain revenue through extracting the trace or potentially deleterious minerals. A more recent driver is the production of a useful product from the tails stream, which has included coarse benign silica sand (Bruckard et al., 2007), the production of iron oxide as a pellet feed from copper tailings at Copiapo, Chile (Jaspers et al., 2008), the use of suitable streams as feed for the manufacture of geopolymers, and many others.

## **Conclusion**

There is an inexorable move in the mining industry towards more sophisticated geostatistical models of the mine, incorporating a wide range of attributes relevant to valuing the project, designing the mine and scheduling production. Particular research attention is being paid at present to geotechnical and mineral processing attributes, and the development of the small scale tests and geostatistical protocols needed to bring these into the block model. It is clear that there is a direct analogy with environmental attributes such as acid and deleterious element drainage potential, and a few operations already include some such aspects in the mine model. The benefits of a successful incorporation of such attributes into formal mine planning include a more accurate assessment of true project value, more sustainable operation and better utilisation of the deposit.

We take the view that recent advances in material testing procedures and advances in mine planning software present a unique opportunity for the development of a robust methodology for including acid and metalliferous drainage potential in the mine plan. The key innovations required are in the area of material characterisation. The specific research areas needing attention include:

- The application of automated SEM-based mineralogy, minor element analysis and textural analysis to define a virtual drainage potential estimate for large numbers of small samples (e.g. drill core).

- A refinement of current static and kinetic tests to make them suitable for making rapid drainage potential estimates on small samples suitable for use in block models. Advances are being made (Stewart et al., 2006) but this is a challenging area.
- Understanding the sampling controls required for these small samples.
- Where necessary, development of modified geostatistical procedures to accommodate the statistical properties of the new attributes, and refinement of mine planning software.
- Development and validation of a robust methodology for including acid and metalliferous drainage potential reliably in the mine model.
- Review of mineral processing strategies for ameliorating drainage potential, in the context of an optimum mine plan.

Work is now underway to develop a proposal for a research project to address these and other environmental issues. A key element will be a multi-disciplinary approach, which is essential if this ambitious but rewarding vision is to be realised.

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### **References**

- Adair B, 2008. Personal communication (DB, JKMRRC).
- Al.T.A., Martin, C.J., and Blowes, D.W. 2000. Carbonate-mineral/water interactions in sulfide-rich mine tailings. *Geochimica et Cosmochimica Acta*. Vol. 64, no. 23, pp. 3933-3948.
- Batista G, 2005. Personal communication (Gemcom Software).
- Beaton, Nick, 2008. Personal communication (Datamine).
- Bennett MW, Kempton HJ, Maley JP, 1997. Applications of geological block models to environmental management. *Proc. 4th Int. Conf. on Acid Rock Drainage (ICARD)*, Vancouver, June, 293-303.
- Bezaazoua, B., Bussieré, B., Dagenais, A.M., Archambault, M. 2004. Kinetic tests comparison and interpretation for prediction of the Joutel tailings acid generation potential. *Environmental Geology*, Vol. 46, pp.1086-1101
- Blowes. D.W. and Jambor. J.L.1990. The pore-water geochemistry and the mineralogy of the vadose zone of sulfide tailings, Waite Amulet, Quebec, Canada. *Applied Geochemistry*, Vol. 5, pp 327-346
- Broadhurst, J L, Petrie, J G and von Blottnitz, H. 2006. Understanding Element Distribution During Primary Metal Production. *Green Processing 2006*, Newcastle, Australia (AusIMM).
- Bruckard, W. J., McCallum, D. A. and Jahanshahi, S. 2007. Treatment of sulfide tailings from base metal and gold operations – a source of saleable by-products and sustainable waste management. *World Gold 2007 Conference*, October.

- Cabri, L.J and Campbell, J.L. 1998. The proton microprobe in ore mineralogy (micro-PIXE technique). In: L.J. Cabri, Editor, *Modern Approaches to Ore and Environmental Mineralogy, Short Course-Mineral. Assoc. Can.* vol. 27 (1998), pp. 181–198.
- Cilliers, J. J. 2006. Active and passive gangue in mineral processing, disposal and economics. IMPC, Istanbul, Turkey.
- Coastech Research Inc. 1989. Investigation of prediction techniques for acid mine drainage. DSS File No. 30SQ.23440-7-9178. Report to Canada Center for Mineral and Energy Technology for Mine Environment Neutral Drainage (MEND) Program. MEND Secretariat, Ottawa, Ontario, Canada.
- Croudace, I.W., Rindby, A. and Rothwell, RG, 2006. ITRAX: description and evaluation of a new multifunction X-ray core scanner. In Rothwell, R.G. (ed.) *New Techniques in Sediment Core Analysis*. Geological Society, London, Special Publications, 267, 51-63.
- DEH, 1997. Managing sulphidic wastes and acid drainage. Australian Government Dept. Environment and Heritage (booklet) – Case Study 2.
- Dobos SK., 2000a. Management of sulfidic mine wastes – current Australian practice and available knowledge and techniques. May (ACMER).
- Dobos SK, 2000b. Potential problems with geologically uncontrolled sampling and the interpretation of chemical tests for waste characterisation and ARD prediction. Proc. 4<sup>th</sup> Australian ARD Workshop, Townsville, ACMER, 25-29.
- Dobos SK and Lee MC, 2000. Industry performance in managing sulfidic mine wastes, the state of ARD management techniques and key areas for strategic research – An Australian perspective. Proc. 4<sup>th</sup> Australian ARD Workshop, Townsville, ACMER, 5-16.
- Dobos SK, 2005. Personal communication.
- Dold B and Fontboté L, 2001. Element cycling and secondary mineralogy in porphyry copper tailings as a function of climate, primary mineralogy, and mineral processing. *J.Geochem.Explor.*, 74, 3-55.
- Dorracott M and Grice AG, 2002. Backfill – the environmentally friendly tailings disposal system. Proc. Green Proc. Conf., Cairns, May (AusIMM), 265-277.
- Dowd PJ, 2005. The business case for prevention of acid drainage. Proc. 5<sup>th</sup> Australian Workshop on Acid Drainage, Fremantle, August (ACMER), 1-10.
- Downing BW and Giroux G. ARD waste rock modeling.  
<http://technology.infomine.com/enviromine/ard/Introduction/BlockModel.htm>
- Downing BW and Giroux G, 1993. Estimation of a waste rock ARD block model for the Windy Craggy massive sulfide deposit, northwestern BC *Explor. and Min. Geo.*, 2 (3), 203-215.
- Downing, B.W. and Madeisky, H.E. 1997. Lithogeochemical methods for acid rock drainage studies and prediction. *Exploration Mining Geology*, vol. 6, Issue 4, pp.367-379.
- Feasby DG and Tremblay GA, 1995. Role of mineral processing in reducing environmental liability of mine wastes. Proc. 27<sup>th</sup> Ann. Meet Can. Mineral Processors, Ottawa, January (CIM), 217-234.
- Fandrich, R., Gu, Y., Burrows, D. and Moeller, K. 2006. Modern SEM-based mineral liberation analysis. *International Journal of Mineral Processing*, 84, p. 310-320.
- Fox, N. 2007. Staining methods to identify potassium feldspar and plagioclase feldspar alteration in Cadia East drillcore. *Unpublished internal report: CODES*, University of Tasmania, p. 1-9.

- Guerny PJ, Morrison RD, Noreen DL. Remediation of acid-sulphate potential in soils by treatment with a hydrocyclone. (JKMRC).
- Hitzman, M.W. 1999. Routine staining of drill-core to determine carbonate mineralogy and distinguish carbonate alteration textures. *Mineralium Deposita*, Vol 34, pp. 794-798.
- Holliday, J. R. and Cooke, D. R., 2007. Advances in Geological Models and Exploration Methods for Copper ± Gold Porphyry Deposits. In Milkereit, B. (ed), 2007, *Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration*, 791-809.
- Hutchison IPG, Ellison RD, 1992, editors. *Mine waste management—A resource for mining industry professionals, regulators and consulting engineers*: Lewis Publishers, 654 p.
- Jaspers, W., Markwath, L. and Parra, F. 2008. Development of an iron ore concentrate fines recovery process from copper tailings 40<sup>th</sup> Canadian Mill Operators Conference, Ottawa.
- Jahanshahi, S., Bruckard, W. J., Chen, C. and Jorge, F. R. A. 2006. Management of Minor Elements in the Production of Base Metals. *Green Processing 2006*, Newcastle, Australia.
- Jambor JL and Blowes DW, 1998. Theory and applications of mineralogy in environmental studies of sulfide-bearing mine wastes in *Modern Approaches to Ore and Environmental Mineralogy* eds- LJ Cabri, DJ Vaughan - 1998 - Mineralogical Association of Canada.
- Jambor JL, Dutrizac JE and Chen TT, 2000. Contributions of specific minerals to the neutralization potential in static tests, in *Proceedings of 5<sup>th</sup> international conference on acid rock drainage*, Denver 21-24 May 2000, 551-565.
- Jambor, J.L. 2003. Mine-waste mineralogy and mineralogical perspectives of acid-base accounting. *In Environmental Aspects of Mine Wastes* editors Jambor, J.L., Blowes, D.W., and Ritchie, A.I.M. Mineralogical Association of Canada. Short Course Series Vol. 31. Chapter 6. 117-147.
- Jenson, E. P. and Barton, M. D., 2000, *Gold Deposits Related to Alkaline Magmatism*. SEG Reviews, Vol. 13, p. 279-314.
- Kelley B, 2005. Personal communication (Rio Tinto).
- Klich, I., Wilding, L. P., and Dress, L. R. 2002. Trace metal and mineral speciation of remediated wastes using electron microscopy. *Anal Bioanal Chem* 372, p. 436 – 443.
- Kolahdoozan M and Yen WT, 2002. Pyrrhotite – an important gangue and a source for environmental pollution. *Proc. Green Proc. Conf., Cairns, May. (AusIMM)*, 245-249.
- Lauder, D W Mavotoi M and Glatthaar, J W. 2003. Fluorine Removal From Ok Tedi Copper/Gold Concentrates. *Eighth Mill Operators' Conference Townsville, Australia*.
- Levington AA, 1974. *Introduction to Exploration Geochemistry*, Applied Publishing, Calgary.
- Lottermoser BG, 2003. *Mine Wastes: Characterisation, Treatment and Environmental Impacts*. Springer, Berlin Heidelberg New York, 277 pp.
- Lyman, G.J., Johnson, N. W. and Guerny, P.J. 2000. Processing refinement to minimise ARD production. *Proceedings of the Fourth Australian ARD Workshop (Australian Centre for Minerals Extension and Research)*, pp 211 - 220.
- Miller GC, Hoonhout C, Miller WW and Miller MM, 1999. Geochemistry of closed heaps: A rationale for drainage water quality, in *Closure, in Remediation and Management of Precious Metals Heap Leach Facilities*, ed. Dorothy Koisich and Glenn Miller, 37-45.
- Miller, S. Robertson, A. and Donahue, T. 1997. Advances in acid drainage prediction using the net acid generating (NAG) Test. *Environmental Geochemistry International Pty Ltd., Balmain, NSW (Australia) 4th International Conference on Acid Rock Drainage*, 31 May-6 June 1997, Vancouver, Canada CANMET, Natural Resources Canada, Ottawa, ON (Canada). Vol 2, 533-549.

- Miller SD, 1998. Predicting acid drainage. *Groundwork*, 2 (September), Australian Minerals and Energy Environment Foundation, 8-9.
- Modis K and Komnitsas K, 2007. Optimum sampling density for the prediction of ARD in an underground sulfide mine. *Mine water and the environment*, 26 (4), Dec., 237-242.
- Morin KA, Hutt NM, 1997. Environmental geochemistry of minesite drainage, MDAG Publishing, Vancouver, British Columbia, Canada.
- Morin, K.A. and Hutt N.M. 1998. Kinetic test and risk assessment for ARD. 5<sup>th</sup> Annual BC Metal Leaching and ARD Workshop, Vancouver, Canada.
- Napier-Munn TJ and Morrison RD, 2003. The potential for the dry processing of ores. *Proc. Conf. on Water in Mining*, Brisbane, Oct. 247-250 (AusIMM).
- Obeng DP and Morrell S, 2003. The JK three-product cyclone-performance and potential applications. *Int. J. Miner. Proc.*, 69 (1-4).
- O'Connor, C.T., Bradshaw, D.J. and Upton. A.E., 1990. The use of dithiophosphates and dithiocarbamates for the flotation of arsenopyrite. *Miner. Engng.*, vol. 3, no 5., pp. 447-459.
- Ohlander, B., Muller, B., Axelsson, M., and Alakanglas, L. 2007. An attempt to use LA-ICP-SMS to quantify enrichment of trace elements on pyrite surfaces in oxidizing mine tailings. *Journal of Geochemical Exploration*. Vol. 92, pp.1-12.
- Plumlee, G.S. 1999. The environmental geology of mineral deposits. In: Plumlee, G.S. and Lodgson, M.J., (eds). *The environmental geochemistry and mineral deposits Part A: processes, techniques, and health issues. Reviews of Economic Geology 6A*. pp 71-113.
- Price WA and Errington JC, 1998. Guidelines for metal leaching and acid rock drainage at minesite in British Columbia. Ministry of Energy and Mines, Government of BC, Aug.
- Robinson B.W., Ware, N.G. and Smith, D.G.W. 1998. Modern electron microprobe trace element analysis in mineralogy. In: L.J. Cabri, Editor, *Modern Approaches to Ore and Environmental Mineralogy, Short Course-Mineral. Assoc. Can.* vol. 27 (1998), pp. 153-179.
- Rossi ME, 2007. Geostatistical uncertainty modelling of acid rock drainage. APCOM, Santiago, 761-767.
- Schwartz, M. O. 1995. Arsenic in porphyry copper deposits: economic geology of a polluting element. *International Geology review*, v37, pp 9-25.
- Shaw, S., and Mills, C. 1998 Acid Rock Drainage, EnviroMine. Website.
- Skousen, J., Renton, J., Brown, H., Evans, P., Leavitt, B., Brady, K., Cohen, L. and Ziemkiewicz, P. (1997), Neutralization Potential of Overburden Samples Containing Siderite, *J. Environmental Quality*, v6, n3, p673-681.
- Sobek A A, Schuller W A, Freeman J R, and Smith R M. 1978. Field and laboratory methods applicable to overburden and mine soils. USEPA Report No. 600/2-78-054, p. 203
- Soregaroli BA and Lawrence RW, 1997. Waste Rock Characterisation at Dublin Gulch: A Case Study, Proceedings of 4<sup>th</sup> International Conference on Acid Rock Drainage, Vancouver, BC, 631-645.
- Tran AB, Miller S, Williams DJ, Fines P, Wilson GW, 2003. Geochemical and mineralogical characterisation of two contrasting waste dumps – the INAP waste dump characterisation project. *Proc. 6<sup>th</sup> ICARD*, Cairns, July, 939-947 (AusIMM).
- Van Berkel R, 2002. Application of cleaner production principles and tools for eco-efficient minerals processing. *Proc. Green Proc. Conf.*, Cairns, May (AusIMM), 57-69.

White, W.W.III., Lapakko, K.A., Cox, R.L. 1999. Static test methods most commonly used to predict acid mine drainage: practical guidelines for use and interpretation. In: Plumlee, G.S. and Lodgson, M.J., (eds). The environmental geochemistry and mineral deposits Part A: processes, techniques, and health issues. Reviews of Economic Geology 6A. pp 325-338.

Whittle D, 2005. Private communication (Whittle Software).