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The process mineralogy of mine wastes

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ABSTRACT

The discipline of process mineralogy developed through the recognition that metallurgical flowsheets could be optimised by thorough characterisation of the precursor ore mineralogy, mineral associations, grain size and textures. In a procedure analogous to process mineralogy it is shown here that effective characterisation of mine wastes for Acid Rock Drainage and Metal(loid) Leaching (ARDML) potential must follow a similar set of robust practices which include: (i) representative sampling; (ii) static/screening level geochemical tests and qualitative mineralogical assessment; (iii) longer-term kinetic geochemical tests and quantitative mineralogical assessment; and (iv) quantitative numerical modelling to assess source term chemistry associated with the mine facilities and thereby determine potential impacts to receptors. This process is dependent on a sufficiently robust drill core database and a detailed mine plan through which an assessment of mine wastes is possible. Such detailed characterisation may be limited by insufficient budgets, however omission of a thorough mineralogical investigation may lead to a lack of understanding of the primary geochemical controls on mine waste behaviour. In turn, this can lead to over- or under-engineering of mine facilities, which can have financial and/or environmental implications. Several case studies are presented to illustrate how mineralogy can be applied to solve problems in ARDML prediction and mitigation, specifically within waste rock assessment.

1. Introduction

Process mineralogy is an integrated discipline which combines quantitative (and qualitative) mineralogical techniques with metallurgical testwork (Lotter et al., 2011). The aim for the process mineralogist is to provide information on specific aspects of the ore mineralogy and mill products and, in so doing, to help the chief metallurgist optimise metallurgical flow-sheets (Henley, 1983). As such, process mineralogy is usually applied to the optimisation of grades and recoveries within a working mine and has been applied to numerous deposit types including gold (Zhou and Gu, 2008), platinum group elements (PGEs) (Cabri et al., 2005) phosphates (Sant'Agostino et al., 2001), uranium (Bowell et al., 2011) and silicon (Grammatikopoulos and Clark, 2001). In brief, the principal features of modern process mineralogical techniques can be divided into four phases; (i) representative sampling; (ii) ore characterisation; (iii) mineralogical assessment and (iv) metallurgical testing. The benefit of applying this robust technique to Acid Rock Drainage and Metal Leaching (ARDML) assessments is twofold. Firstly, process mineralogy has provided real and measurable improvements in flowsheet optimisation and grade-recovery problem shooting (e.g. Charland et al., 2006; Lotter et al., 2003). Secondly the offshoot of getting an ARDML assessment wrong has the potential for major effects (including contaminated fishery sources, contaminated water, habitat destruction and livelihood disruption where the potential is underpredicted and conversely excessive and unnecessary engineering if over prediction occurs). By using the same flowsheet it is anticipated that similar improvements in mine waste assessment, handling and eventual effective disposal and management can be achieved, particularly if mineralogy investigations are fully integrated with kinetic (long-term) geochemical testwork.

2. Process mineralogy for ARDML

ARDML refers to the generation of acidic, metal and/or sulfate-rich waters that result from the weathering of sulfide minerals (particularly pyrite/marcasite – FeS_2) under oxidising conditions (Evangelou and Zhang, 1995; Nordstrom, 1982; Nordstrom and Alpers, 1999). The process may occur naturally in sulfide-bearing rock strata, but is commonly accelerated by mining activities, which increases the likelihood of exposure of sulfide minerals to air and water, effectively accelerating natural weathering processes.

In the context of ARDML the minerals that are considered deleterious are sulfide minerals and, to a lesser extent, minerals such as elemental sulfur and hydroxyl-sulfates (e.g. jarosite, alunite). By far the most common sulfide mineral within many mineral

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deposits is pyrite (FeS_2), which due to its relative abundance is usually the greatest contributor to ARDML (Nordstrom and Alpers, 1999). Other sulfides that may be commonly observed and which may contribute to ARDML include, pyrrhotite ($Fe_{1-x}S$), bornite (Cu_5FeS_4), arsenopyrite (FeAsS), realgar (As_4S_4), orpiment (As_2S_3), stibnite (Sb_2S_3), sphalerite (ZnS), galena (PbS) and chalcopyrite ($CuFeS_2$) (Plumlee, 1999).

The composition and distribution of sulfide minerals will vary depending on the nature of the host rocks, with some deposits largely barren of sulfides (e.g. some iron–magnetite skarns) whilst others contain substantial amounts (e.g. volcanogenic massive sulfide (VMS) deposits). Indeed within a deposit the amount of sulfides may vary in terms of abundance, type and texture as the host rock varies or cross-cutting features such as dykes and veins bring in or disrupt sulfide mineralisation (Plumlee, 1999). In particular it is important to consider the texture of sulfide mineralisation and its textural relationships with other minerals (e.g. silicates, carbonates), as this is likely to have implications for the long-term weathering behaviour of the waste (Parbhakar-Fox et al., 2011). It is also necessary to consider that the nature of the proposed waste rock may vary over the course of the life of mine as mining methods change (e.g. open pit to underground mining) or as new resources are developed. It is best if such site-specific requirements are considered before mine development and re-considered during changes in operation and through to mine closure (e.g. (INAP, 2010)).

An additional component of any mineralogical assessment is the assessment of the textures and abundances of any neutralising minerals which will counteract the negative products of sulfide oxidation (namely; acidity, sulfur species, total dissolved solids and metal(loid)s). The reactivity of the neutralising minerals determines their effectiveness at which any acidity can be buffered. This reactivity varies widely, with most carbonate minerals being very effective acid consumers but with other minerals such as the "pyroboles" (Ca–Mg amphiboles, pyroxenes and micas) providing more long-term neutralising potential (e.g. Jambor, 2003; Nesbitt and Jambor, 1998); Table 1). In general, effective neutralisation potential requires the abundant presence of carbonate minerals (typically a threefold excess compared to sulfide minerals) (INAP, 2009).

Table 1
Typical neutralisation potential (NP) values and pH buffering ranges for some common minerals (Blowes et al., 2003; INAP, 2010; Jambor, 2003). Me = monovalent, divalent or trivalent cation.

Group	Formula	Buffer pH	Neutralisation potential range (kg)
Carbonates			500–1350
Calcite/aragonite	$CaCO_3$	5.5–6.9	
Siderite	$FeCO_3$	5.1–6.0	
Malachite	$Cu_2CO_3(OH)_2$	5.1–6.0	
Oxides			
Gibbsite	$Al(OH)_3$	3.7–4.3	
Goethite	FeOOH	3.0–3.7	
Ferrihydrite	$Fe(OH)_3$	2.8–3.0	
Jarosite	$KFe_3(SO_4)_2(OH)_6$	1.7–2.0	
Aluminosilicates		0.5–1.5	
Feldspar Group			
K-Feldspar	$(K,Na)AlSi_3O_8$		0.5–1.4
(Ab100–Ab50) Albite	$NaAlSi_3O_8$		0.5–2.6
(An51–An100) Anorthite	$CaAl_2Si_2O_8$		5.3–12.5
Pyroxene group	$(Me)(Si,Al)_2O_6$		0.5–9.5
Amphibole group	$(Me)_{7-8}((Si,Al)_4O_{11})(OH)_2$		0.2–8.1
Mica group			
Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$		0.3
Biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$		2.7–8.8
Chlorite	$(Mg,Fe,Al)_6(Al,Si)_4O_{10}(OH)_8$		0.8–21.6
Clay group	$(Me)(Si,Al)_4O_{10}(OH)_2$		2.7–29.0
Garnet group	$(Ca, Mg, Fe, Mn)_3(Al, Fe, Cr)_2(SiO_4)_3$		1.3–6.3
Apatite group	$Ca_5(PO_4)_3(F,Cl,OH)$		2.7–11.3
Miscellaneous			
Talc	$Mg_3Si_4O_{10}(OH)_2$		1.7
Serpentine	$Mg_6Si_4O_{10}(OH)_8$		15.1–87.6
Epidote	$Ca_2(Al,Fe)_3Si_3O_{12}(OH)$		1.0–3.0
Wollastonite	$CaSiO_3$		440

If waste-rock is liable to produce acid then pH tends to decrease along a series of plateaus, where each plateau is controlled by buffering to a series of mineral assemblages (Fig. 1). Since this figure was produced it has become apparent that neutralisation can occur at higher pHs through ultramafic mineral assemblages, providing they are present in sufficient abundance (Nesbitt and Jambor, 1998). It is important to note that the weathering of acid-buffering carbonate and silicate minerals in this way may result in a lag time before acid-generating conditions are produced (see Fig. 1), even in material that will eventually be highly acid-generating. Caution must therefore be practised when interpreting the early results of static geochemical characterisation testing, and it is here that adequate mineralogical characterisation may play an important role in interpreting analytical results.

If left unmitigated, ARDML can be environmentally and socially destructive, potentially causing both short-term and long-term impacts, which may be subsequently very expensive to clear-up (Price, 2003, 2009). As such, the correct characterisation of potential waste rock and tailings is necessary during the early stages (pre-feasibility and feasibility) of mine planning. This will allow the implementation of any necessary mitigation measures to minimise potential impacts to the environment as well as result in potential long-term cost savings. The use of mineralogy within ARDML assessments and waste rock characterisation has developed rapidly over the last two decades with numerous case studies (e.g. Blowes and Jambor, 1990; Downing and Madeisky, 1997; Goodall, 2008; Lindsay et al., 2009; Paktunc, 1999; Parbhakar-Fox et al., 2011) illustrating the integral nature of mineralogy within a standardised ARDML characterisation and prediction study (Verburg et al., 2009).

Despite these advances, the full systematic integration of mineralogical techniques within ARDML assessments still requires some development that takes into account factors such as representative sampling (e.g. (Lotter et al., 2011), and a thorough mineralogical textural analysis (e.g. Parbhakar-Fox et al., 2011). It is argued that assessment of ARDML potential is best carried out using a procedural flowsheet analogous to a typical process mineralogical flowsheet. This has been split into four phases, namely (i) representative sampling, (ii) static/screening level geochemical characterisation tests with qualitative mineralogical assessment, (iii) longer-term kinetic geochemical tests with quantitative mineralogical assessment; and (iv) quantitative numerical modelling with mitigation recommendations (Fig. 2). In particular it is argued that the current use of mineralogy within mine waste assessments is not fully integrated with Phase 3 of this flowsheet. Mineralogy plays a key role in the first three phases and these will each be considered in turn. Several case studies have been presented which highlight the requirement for mineralogical characterisation within ARDML assessments.

2.1. Phase 1 – representative sampling

Sampling of representative waste rock can be best performed using available drill core from the exploration program (given the availability of a robust drill-core database). As with metallurgical

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