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TECHNICAL ARTICLE

Improving Management of Potentially Acid Generating Waste Rock

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Abstract Managing the appropriate disposition of waste rock is a critical function of hard rock mining given the propensity of some materials to be acid-generating and the increasing environmental stewardship role of the mining industry. At most Newmont Mining Corporation mine sites, the net carbonate value (NCV) classification is used to partition mine waste according to acid generating potential; these are often further segregated into seven material types ranging from 'highly acidic' to 'highly basic'. Although the NCV classification is generally a good predictor of acid-generating potential, humidity cell test (HCT) results for the NCV types 'slightly basic' and 'inert/neutral' were occasionally anomalous compared to the anticipated NCV-based acid-generating potential because acid generated by soluble aluminum and iron sulfates was not accounted for in the NCV test. This study was undertaken to develop an improved waste rock acid estimator using a battery of tests and to develop appropriate termination criteria for HCTs used to determine the potential for acid generation by waste rock. The HCTs were assessed for net alkalinity, pH, a molar ratio of (Ca + Mg/sulfate), and carbonate dissolution versus pyrite oxidation rates for HCTs over the 20 week period and/or the HCT forecast after 20 weeks. The results of HCTs compared with a combination of NCV, paste pH, and net acid generation (NAG) pH represents a simple tool to enhance screening run-of-mine waste for disposition to an appropriate storage location.

Keywords Acid generation potential · Acid mine drainage · Kinetic test · Mine waste · Static test · Stored acidity

Introduction

The formation of acid rock drainage (ARD) and the derived solutes have been described as the largest environmental problem facing the mining industry (US EPA 1994). Iron sulfides generate acid and release sulfate and heavy metals to the environment when exposed to air and water, if not managed appropriately. The intensity and duration of ARD are complex functions of mineralogy, hydrology, geology, and climatic conditions (White et al. 1999). The primary factor influencing the pH of ARD is the balance between a rock's neutralization capacity from carbonate minerals and its propensity for sulfide minerals to oxidize and generate acidity. In addition, common products of sulfide oxidation like soluble sulfates, hydrous sulfates, and some hydroxysulfates (e.g. melanterite, jarosite, or alunite) are also of environmental interest because they may store acid and metals; their dissolution may result in flushes of acid and metals to ground and surface waters (Nordstrom and Alpers 1999; Plumlee 1999). Consequently, reliable predictive methods to determine acid-generating potential for mine waste materials are required both by the mining industry and regulators (White et al. 1999).

Currently, a number of static and kinetic geochemical testing methods to estimate acid-generating potential and acidity are available. Static testing methods are short term (hours to days) and relatively low cost (≈$50–135 each),

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while kinetic testing methods are long term (months to years) and more expensive (≈$3,000–5,000 per test over 20 weeks). Static testing methods (e.g. acid–base accounting (ABA), net carbonate value (NCV), paste pH, net acid generation (NAG) pH estimate the capacity of mine waste materials to produce acid, and measure any acidity present, and the potential to neutralize acid. However, static tests do not provide any information on dissolution rates of acid-generating and acid-neutralizing minerals. In contrast, most kinetic testing methods (e.g. humidity cell tests or HCTs) estimate rates of sulfide oxidation and neutralizing mineral dissolution which, in turn, are used to forecast leaching over long periods of time. The use of HCTs to estimate dissolution rates requires at least 20 weeks of elapsed time (ASTM 1996, 2007a). Recently, concern has been raised regarding the appropriate duration of HCTs. For example, the Global Acid Rock Drainage 2009 manual (http://www.gardguide.com) cites one case where an HCT became acidic only after 150 weeks into the test. In this contribution, we also assessed our HCT results to determine if HCTs should be run for longer than the minimum 20 week period (ASTM 2007a), and if so, when they can be reasonably terminated.

Currently, the NCV method (based on sulfide and carbonate content) is used by Newmont Mining Corporation (NMC) as an indicator of the acid-generating and acid-neutralizing potential of mine waste materials (discussed below). Following NMC standard NCV classification, mine waste materials are differentiated into seven NCV types, from 'highly acidic' to 'highly basic' (Table 1). This method was developed by Newmont Metallurgical Services (NMS) for material selection from waste types to determine the disposition of waste rock during active mine operations (http://www.bucknam.com/ncv.html) and has been standardized as the American Society for Testing and Materials method E 1915-07 (ASTM 2007b). However, due to the complexity of the chemical, physical, and biological processes involved in acid-generating and acid-neutralizing mineral dissolution, no single method (i.e. NCV) has proven completely accurate to measure both acid generation potential due to sulfide minerals and acid stored as acidic sulfates, when compared to HCTs.

Table 1 Newmont mining corporation net carbonate value (NCV) type classification and it's conversion to net neutralization potential (NNP)

NCV type	NCV criteria (% CO_2)	NNP criteria (g/kg $CaCO_3$)
Highly acidic	$-5 \le$ NCV	$-113.5 \le$ NNP
Acidic	$-5 <$ NCV ≤ -1	$-113.5 <$ NNP ≤ -22.7
Slightly acidic	$-1 <$ NCV ≤ -0.1	$-22.7 <$ NNP ≤ -2.27
Neutral/inert	$-0.1 <$ NCV < 0.1	$-2.27 <$ NNP < 2.27
Slightly basic	$0.1 \le$ NCV < 1	$2.27 \le$ NNP < 22.7
Basic	$1 \le$ NCV < 5	$22.7 \le$ NNP < 113.5
Highly basic	$5 \le$ NCV	$113.5 \le$ NNP

Previously, a combination of static tests, i.e. ABA and NAG pH has been used to determine acid-generating potential for mine waste rocks and tailing samples in the Ashanti Belt, Ghana (Akabzaa et al. 2007). Although the study indicated that a combination of ABA and NAG pH is sufficient to screen mine samples for their acid generating potential, this method has not yet been validated against kinetic test results or field data (Akabzaa et al. 2007). Therefore, our study was conducted to evaluate several potential combinations of static tests (NCV, NAG pH, and paste pH) with the objective of improving the predictive accuracy of the NCV-only predictor for 'inert/neutral' and 'slightly basic' samples, based on the NMC standard NCV classification. The results from these combinations were validated against the HCT results using a subset of the same samples to estimate the possible leachate quality. Our HCTs were conducted according to ASTM method D 5744-07 (ASTM 2007a) to provide a 20-week record of weathering reaction product mass release, including acidity and alkalinity. This contribution appears to be the first to develop a simple predictive method to determine the appropriate disposition of waste rock into either a potentially acid generating (PAG) facility, or for use as pit backfill or in a conventional aerial waste rock facility without compromising operational efficiency.

Materials

All samples used in this study were collected from the Genesis mine area, 18 miles northwest of Carlin, Nevada. The mine is located in a northwest-southeast trend between the Leeville and Post/Betze mines along the Tuscarora spur of the Tuscarora Mountains (Fig. 1). The stratigraphy of the Genesis mine consists of the autochthonous Siluro-Devonian Roberts Mountains Formation, Devonian Popovich Formation, and Devonian Rodeo Creek unit. The lithology varies from carbonates lower in the section to increasingly siliceous rocks higher in the section. The autochthonous sequence is structurally overlain along the Roberts Mountain thrust by an allochthonous package of penetratively sheared mudstone and quartz hornfels of the Ordovian Vinini Formation. The Genesis mine lithology (siliceous and carbonate rocks) was subdivided into six alteration types, including oxide siliceous (OS), unoxidized siliceous (US), oxide carbonate (OC), oxide carbonate decalcified (OCD), unoxidized carbonate (UC), and unoxidized carbonate decalcified (UCD). The dominant alteration associated with mineralization within the carbonates is decalcification (OCD and UCD) with accompanying

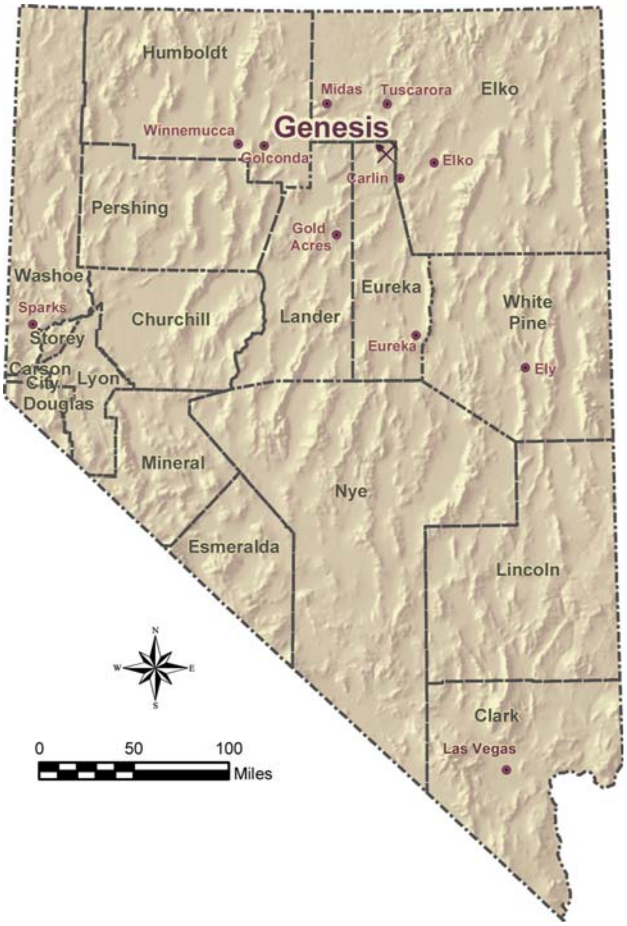

Fig. 1 Location of Genesis mine

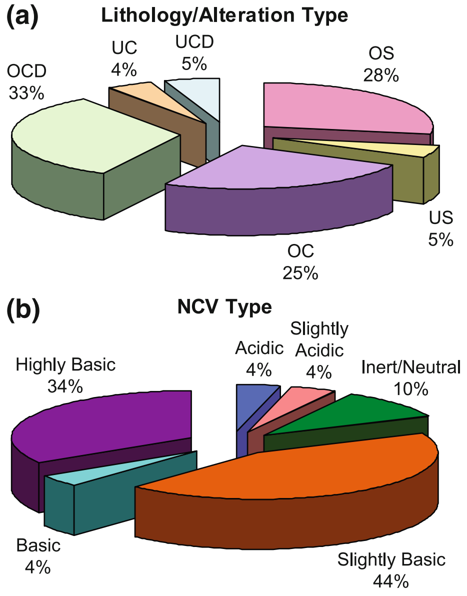

Fig. 2 The distribution of waste rock in Genesis mine based on **a** lithology/alteration and **b** net carbonate value (NCV) types

minor silicification, clay alteration, and quartz-sericite-pyrite alteration. Sulfide deposition accompanied these alteration events.

The total waste rock tonnage from the Genesis mine area will be ≈400 million tonnes (440 million US tons), comprising OCD (33%), OS (28%), OC (25%) with US, UC, and UCD each at 5% or less (Fig. 2a). Based on the NCV type, waste rock will consist of 4% acidic, 4% slightly acidic, 10% inert/neutral, 43% slightly basic, 4% basic, and 34% highly basic (Fig. 2b).

In order to develop a representative characterization of mine waste rock chemistry, samples from each NCV, lithology, and alteration type to be mined in the study area were collected from exploration drilling rejects. From 3,400 boreholes in and around the deposit, 15,000 individual samples were analyzed for NCV, from which 533 samples were composited according to similar NCV, lithology, and alteration types to engender the 34 composites providing the basis for this study. All major combinations of lithology, alteration, and NCV type present at the mine site (Fig. 2) are represented in this suite (Table 2).

Methods

Several static tests were conducted on splits of the 34 composite samples, including NCV, NAG pH, and paste pH. Twenty of the 34 samples representing major combinations of lithology, alteration, and NCV type present at the mine site were selected for HCTs. Due to the relatively low tonnage of waste rock among the same NCV type, the samples representing US inert/neutral (0.4%), US slightly basic (1.3%), and the known neutralizing UC highly basic (4.4%) were not carried through to the HCT phase of the study. Therefore, the discussion of static and kinetic test results in this study focus on the selected 20 composite samples which represent 94% of all waste rock that will be produced.

Net Carbonate Value

The process of calculating NCV differs from the Sobek ABA method (Sobek et al. 1978) because acid-neutralizing potential (NP) and acid-generating potential (AP) are determined by combustion infrared absorption spectrometry, ASTM method E 1915-07 (ASTM 2007b). NCV determination is based on units of % CO_2, based on certified standard reference materials with known CO_2 content for quality assurance and compliance purposes (http://www.bucknam.com/ncv.html; ASTM 2007b). The NP is calculated based on the carbonate carbon content, which is determined by the difference between total carbon (CTOT) and residual carbon after reaction with HCl (CAI):

Table 2 Relationship of Genesis lithology, alteration, and NCV types

Lithology	Alteration type	NCV type	ID	Waste rock (tonnes)
Siliceous rock	Oxide siliceous (OS)	Inert/neutral	**15, 16**, 18, **19, 20**, 24	16,250,000
		Slightly basic	13, 17, 22, **23**	86,300,000
		Basic	14, **21**	8,700,000
	Unoxidized siliceous (US)	Acidic	28, **30**	5,900,000
		Slightly acidic	**31**, 32, 35	4,500,000
		Inert/neutral	29	1,775,000
		Slightly basic	33	5,285,000
		Basic	**34**	1,710,000
Carbonate rock	Oxide carbonate (OC)	Basic	**3**	6,335,000
		Highly basic	**1**, 2, **4**	93,160,000
	Oxide carbonate decalcified (OCD)	Inert/neutral	**5, 7, 11**	23,640,000
		Slightly basic	**6, 8**, 12	82,240,000
		Highly basic	**10**	25,310,000
	Unoxidized carbonate (UC)	Highly basic	25	17,400,000
	Unoxidized carbonate decalcified (UCD)	Acidic	**26**	9,670,000
		Slightly acidic	**27**	11,840,000

Composite ID in bold was chosen for kinetic tests

$$\mathrm{NP}(\%\,\mathrm{CO_2}) = 3.67 \times \%\ \text{carbonate carbon content} \tag{1}$$

$$\mathrm{NP}(\%\,\mathrm{CO_2}) = 3.67 \times (\mathrm{CTOT} - \mathrm{CAI}) \tag{2}$$

AP is determined from sulfide sulfur by the difference between total sulfur (STOT) and sulfur after pyrolysis at 550°C (SAP) to liberate sulfate and organic sulfur:

$$\mathrm{AP}(\%\,\mathrm{CO_2}) = -1.37 \times \%\ \text{sulfide sulfur} \tag{3}$$

$$\mathrm{AP}(\%\,\mathrm{CO_2}) = -1.37 \times (\mathrm{STOT} - \mathrm{SAP}) \tag{4}$$

NCV is calculated by adding AP and NP:

$$\mathrm{NCV}(\%\,\mathrm{CO_2}) = \mathrm{NP} + \mathrm{AP} \tag{5}$$

Any reported negative values for NP and positive values for AP (neither of which are theoretically possible but occasionally occur at detection limit values) are corrected to zero before calculating the NCV. The results of NP, AP, and NCV in % CO_2 can be converted to g/kg $CaCO_3$ or kg/tonnes $CaCO_3$ by multiplying by 22.7.

Mineral identification was performed on 20 composite samples by semi-quantitative X-ray diffraction (XRD) analysis and on 17 composite samples by X-ray modal mineral liberation analysis, primarily for sulfides and trace metals (XMOD-MLA). The lower limit of XRD detection is generally 1%, but can be 5% or higher for minerals yielding relatively low intensity X-ray peaks, while the detection limits of MLA for targeted minerals is <0.01%. The XRD results were used to derive mineral AP and NP when pyrite or carbonate minerals were present at $\geq$5%; otherwise, MLA results were used in the analysis. The mineral AP and NP were then compared to the static test AP and NP to estimate the accuracy of the AP and NP estimates.

Mineral-based NP was calculated based on the carbonate carbon content (% C) from calcite and dolomite, i.e.:

$$\%\,\mathrm{C} = (0.12 \times \%\,\text{calcite}) + (0.13 \times \%\,\text{dolomite}) \tag{6}$$

$$\mathrm{NP}\,(\%\,\mathrm{CO_2}) = 3.67 \times \text{carbonate carbon} \tag{7}$$

AP is determined from the pyrite content, i.e.:

$$\text{sulfide sulfur}\,(\%\,\mathrm{S}) = 0.53 \times \%\,\text{pyrite} \tag{8}$$

$$\mathrm{AP}\,(\%\,\mathrm{CO_2}) = -1.37 \times \text{sulfide sulfur} \tag{9}$$

and the NCV was calculated by adding AP and NP using Eq. 5. Potential neutralization from feldspar silicates were excluded due to a lack of C in these minerals.

Paste pH

Paste pH was measured to determine short term acid-neutralizing and acid-generating potential based on acid released by dissolution of soluble sulfates (e.g. melanterite, jarosite, and alunite). Sulfide oxidation reactions are time dependent; therefore, one time paste pH results alone provide little indication of the propensity of a sample to produce acid due to sulfide oxidation.

Paste pH was measured using the American Society of Agronomy (ASA) Monograph 9 method (http://www.svl.net/analysis.html). The samples were mixed with deionized water (1:1 ratio) for 60 min, and the pH of the resulting slurries measured. To assess the acid-generating potential due to dissolution of acidic sulfates, the slurry pH was compared to the pH of deionized water (pH $\approx$ 5.5–6). If the slurry pH was >6, the sample was classified as non-acid generating.

Net Acid Generation pH

Not all sulfides are necessarily available or reactive, and acidity generated by peroxide oxidation of sulfides may be immediately neutralized by carbonate minerals present in the sample, or limited if encapsulated in siliceous hosts, e.g. quartz, plagioclase, etc. Therefore, NAG pH was used to determine the acid-generating potential of reactive sulfide minerals in excess of neutralizing carbonates. The solid material (1%) was reacted with 15% hydrogen peroxide (H_2O_2) with an initial pH of 4.5 for several hours, and the final pH was then measured as a NAG pH value. If the resulting NAG pH was <4.5, the material was classified as acid-generating, while material with a net acid neutralization pH $\geq$ 4.5 was classified as non-acid-generating (Miller 1998).

Humidity Cells

HCTs were conducted on 1 kg of each composite sample, with a particle size <6.3 mm (80% of particle size <2 mm), following ASTM method D5744-07 Option A (ASTM 2007a). Dry, filtered, compressed air (atmospheric) was pumped through the cells for 3 days, a humidifier was then added in-line and the cells received humid air for 3 days. On the seventh day, airflow to the cells ceased and the cells were leached by adding a mass of deionized water equal to the mass of sample to the cell with the water remaining in the cell for 1 h before being drained. The weekly cycle was resumed by restarting dry airflow to the cells. HCTs were operated on this cycle for 20 weeks and then terminated because the pH, alkalinity/acidity, Ca, Mg, and sulfate for most samples had stabilized.

The leachate was collected in sealed, amber, boro-silicate glass bottles and volumes were weighed. Unfiltered, unpreserved leachate samples were analyzed immediately for redox potential (ORP), pH, electrical conductivity (EC), sulfate, total dissolved solids (TDS), acidity, and alkalinity. Separate leachate samples were filtered through 0.45 μm membrane filters and analyzed for Fe (total and ferrous), Ca, and Mg. Additionally, an unpreserved sample and a nitric acid preserved sample from weeks 0, 1, 2, 4, 8, 12, 16, and 20 were analyzed for NDEP Profile I analysis (http://www.svl.net/analysis.html).

To determine whether a sample was acid generating, a combination of the measured total alkalinity/acidity, pH, Ca, Mg, and sulfate was assessed. The mass release of Ca, Mg, and sulfate from the HCTs, with the corresponding total sulfur and carbonate from the NCV method were used to predict future carbonate dissolution and pyrite oxidation rates following EPA method 1627 (US EPA 2009). The 'life expectancy' of pyrite and carbonate minerals was derived from the best-fit lines to these data.

Geochemical Modeling

Geochemical modeling was conducted to identify solid phases that could be precipitated during HCTs. All calculations used the equilibrium code PHREEQC, version 2.12.1 (Parkhurst and Appelo 1999), with the MINTEQ.DAT (Allison et al. 1991) thermodynamic database. The complete leachate chemistry analyzed during the HCTs at week 0, 1, 2, 4, 8, 12, 16, and 20 was used in the simulations.

Results

Splits of the homogenized subset of 20 samples that represent the majority (94%) of the waste rock volume to be mined at the Genesis area were analyzed for NCV, mineralogy (by XRD and MLA,) paste pH, NAG pH, and HCTs.

Net Carbonate Value

The NCV ranged from −1.9 to 14% CO_2 (NNP −42 to 314 g/kg $CaCO_3$), covering the acidic to highly basic range based on the NMC standard NCV protocol (Table 3). Composites 20, 26, 27, 30, and 31 showed negative NNP values characteristic of the acidic or slightly acidic code, although 20 were classified as inert/neutral. Of the 20 samples, 11 did not contain AP; NP values ranged from 0 to 14% CO_2 (314 g/kg $CaCO_3$).

Recent ABA classifications for non-acid, uncertain, and acid materials are based on both the NNP and NP/AP ratio (Table 4). The range considered to be non-PAG material by regulatory agencies in Nevada differs between the Nevada Bureau of Land Management (BLM 1996) and the Nevada Department of Environmental Protection (NDEP 1990). BLM (1996) guidelines indicate that material with NNP > 20 g/kg $CaCO_3$ and NP/AP > 3 is unlikely to generate acid. Where NNP $\leq$ 20 g/kg $CaCO_3$ and/or NP/AP $\leq$ 3, the material is categorized as uncertain, which may trigger kinetic testing of the material. Of the 20 samples in this study, 6 composites (1, 3, 4, 10, 21, and 34) met or exceeded the BLM criteria for non-PAG material, which under the NMC standard NCV system are classified as basic and highly basic.

Table 3 Acid–base accounting results for Genesis samples

ID	NCV type	CTOT (% C)	CAI (% C)	CTOT-CAI (% C)	STOT (% S)	SAP (% S)	STOT-SAP (% S)	NP (% CO_2)	NP (g/kg $CaCO_3$)	AP (% CO_2)	AP (g/kg $CaCO_3$)	NCV (% CO_2)	NNP (g/kg $CaCO_3$)	NP/AP	NP/AP*	BLM criteria	NDEP criteria
1	Highly basic	3.5	0.1	3.4	0.1	0.2	0.00	12.4	281.7	0.00	0.00	12.4	281.7	No AP	1240.8	Non acid	Non acid
3	Basic	1.0	0.2	0.8	0.3	0.2	0.03	3.0	67.7	−0.04	−1.0	2.9	66.8	70.25	70.3	Non acid	Non acid
4	Highly basic	4.1	0.3	3.8	0.3	0.3	0.00	13.9	314.4	0.00	0.00	13.9	314.4	No AP	1385.1	Non acid	Non acid
5	Inert/neutral	0.6	0.5	0.02	0.09	0.1	0.00	0.07	1.5	0.00	0.00	0.07	1.5	No AP	6.6	Uncertain	Non acid
6	Slightly basic	0.7	0.6	0.07	0.2	0.2	0.00	0.3	5.8	0.00	0.00	0.3	5.8	No AP	25.7	Uncertain	Non acid
7	Inert/neutral	0.3	0.3	0.02	0.1	0.1	0.00	0.06	1.3	0.00	0.00	0.06	1.3	No AP	5.9	Uncertain	Non acid
8	Slightly basic	1.4	1.4	0.06	0.1	0.1	0.00	0.2	4.7	0.00	0.00	0.2	4.7	No AP	20.6	Uncertain	Non acid
10	Highly basic	1.5	0.03	1.4	0.2	0.2	0.00	5.2	118.5	0.00	0.00	5.2	118.5	No AP	521.9	Non acid	Non acid
11	Inert/neutral	0.2	0.2	0.01	0.4	0.4	0.00	0.05	1.1	0.00	0.00	0.05	1.1	No AP	4.8	Uncertain	Non acid
15	Inert/neutral	0.3	0.3	0.00	0.07	0.09	0.00	0.01	0.2	0.00	0.00	0.01	0.2	No AP	0.7	Uncertain	Uncertain
16	Inert/neutral	0.5	0.5	0.00	0.07	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.0	No AP	1.0	Uncertain	Uncertain
19	Inert/neutral	0.4	0.4	0.03	0.2	0.1	0.04	0.1	2.4	−0.05	−1.24	0.05	1.2	1.94	1.9	Uncertain	Non acid
20	Inert/neutral	0.9	0.9	0.00	0.3	0.2	0.06	0.01	0.2	−0.08	−1.83	−0.07	−1.6	0.14	0.1	Uncertain	Uncertain
21	Basic	1.2	0.7	0.5	0.5	0.4	0.1	1.7	38.7	−0.2	−4.04	1.5	34.6	9.56	9.6	Non acid	Non acid
23	Slightly basic	0.3	0.2	0.09	0.07	0.1	0.00	0.3	7.2	0.00	0.00	0.3	7.2	No AP	31.9	Uncertain	Non acid
26	Acidic	0.6	0.5	0.01	2.4	1.0	1.4	0.04	0.9	−1.9	−43.01	−1.9	−42.1	0.02	0.0	Uncertain	Uncertain
27	Slightly acidic	0.8	0.8	0.01	0.9	0.4	0.4	0.04	0.9	−0.6	−13.28	−0.5	−12.4	0.07	0.1	Uncertain	Uncertain
30	Acidic	0.6	0.6	0.04	1.7	0.3	1.4	0.2	3.6	−1.9	−43.20	−1.7	−39.6	0.08	0.1	Uncertain	Uncertain
31	Slightly acidic	0.5	0.3	0.2	1.2	0.4	0.8	0.6	14.2	−1.1	−24.20	−0.44	−10.0	0.59	0.6	Uncertain	Uncertain
34	Basic	1.0	0.04	1.0	1.5	0.7	0.8	3.5	79.6	−1.1	−24.88	2.4	54.7	3.20	3.2	Non acid	Non acid

CTOT total carbon, *CAI* residual carbon after reaction with HCl, *CTOT-CAI* carbonate content, *STOT* total sulfur, *SAP* sulfur after pyrolysis at 550°C, *STOT-SAP* sulfide content, *NP* acid-neutralizing potential, *AP* acid-generating potential, *NCV* net carbonate value, *NNP* net neutralization potential. BLM criteria is NNP $>$ 20 g/kg $CaCO_3$ and NP/AP $>$ 3. NDEP criteria for acid-neutralizing potential is NP/AP $>$ 1.2. Negative NP and positive AP are corrected to zero before NCV calculation. NP/AP* are calculated using detection limit value

Table 4 Interpretation of acid-generating potential based on NNP and NP/AP

Acid–base accounting	Acid	Uncertain	Non-acid
NNP (g/kg $CaCO_3$):			
Appalachian coal-mine criterion[a]	≤ -5	ND	ND
BC metal mine criterion[b]	≤ 0	ND	ND
Ferguson and Morin (1991)	ND	$-20 < NNP < 20$	ND
Day (1989)	<10	ND	ND
Newmont criterion[c]	<−2.27	$-2.27 \leq NNP < 2.27$	>2.27
BLM criterion[d]			>20
NP/AP:			
Brodie et al. (1991)	<1	$1 < NP/AP < 3$	>3
Morin and Hutt (1994)	<1	$1 < NP/AP < 1.3–4$	>1.3–4.0
BLM criterion[d]			>3
NDEP criterion[e]			>1.2

NP acid-neutralizing potential, *AP* acid-generating potential, *NNP* net neutralization potential, *ND* not defined in reference

[a] Sobek et al. (1978); [b] Ferguson and Morin (1991); [c] Newmont Metallugical Services (ASTM 2007b); [d] BLM (1996); [e] NDEP (1990)

In contrast, NDEP (1990) guidelines categorize material with a NP/AP > 1.2 as non- PAG. Of the 20 composites in this study, 12 (1, 3, 4, 5, 6, 7, 8, 10, 11, 21, 23, and 34) met or exceeded the NDEP criteria for non acid-generating. Under the NMC standard NCV system, these samples are classified as slightly basic, basic and highly basic, with several in the inert/neutral category.

Mineralogy

Based on XRD, the highly basic samples (1, 4, and 10) contained more calcite (up to 35%), dolomite (up to 14%), and pyroxene (diopside; up to 27%) than the other codes (Table 5). The basic composites (21 and 34) contained 2–3% carbonate, siderite (4–6%), and 1–3% pyrite (Table 5). The slightly basic composites (6 and 23 but not 8) contained <0.08% (by MLA) of calcite, dolomite, and jarosite (Table 5). Sulfides were detected by MLA in 6 (0.01%) and 8 (0.08%), but not in 23. The inert/neutral composites (5, 7, 15, 16, 19, and 20) contained on average 1.7% iron oxide, 13% illite, 0.05% pyrite, and As-rich pyrite, and 0.05% alunite. By MLA, 11 contained <0.01% pyrite; jarosite was present in composites 5, 15, 19, and 20, and alunite was present in 5, 7, 11, 16, 19, and 20.

The slightly acidic composites (27 and 31) contained 0.7 and 1.3% of pyrite, respectively by MLA and 1 and 2%, respectively by XRD. In these samples, calcite in composite 31 (0.03%), and dolomite (0.01–0.03%) occurred at the MLA detection limit at similar concentrations as in the inert/neutral samples (Table 5). The acidic composites (26 and 30) contained more pyrite and As-rich pyrite (3% by XRD) than the other NCV codes (Table 5).

The XRD and MLA data were used to estimate the mineral NP, AP, and NNP based on pyrite, calcite, and dolomite, assuming the higher concentration where both methods returned a value (Table 5). The PAG sulfates (e.g. jarosite, or alunite) were excluded in the mineral AP calculation to allow direct comparison with the chemical AP (which is based only on sulfide), while siderite was excluded from the NP calculation because of possible generation of acid during iron hydrolysis (White et al. 1999). The dissolution of siderite can release aqueous ferrous iron, which in conjunction with the precipitation of ferric hydroxide [$Fe(OH)_3$] from ferrous iron oxidation can decrease the solution pH, e.g.:

$$FeCO_3 + H^+ \rightarrow Fe^{2+} + HCO_3^- \quad (10)$$

$$Fe^{2+} + 1/4O_2 + 5/2H_2O \rightarrow Fe(OH)_3 + 2H^+ \quad (11)$$

Using the mineralogic data, the computed NCV values (Table 6) from −1.5 to 15% CO_2 (NNP −35 to 350 g/kg $CaCO_3$) are generally in good agreement with those determined analytically, −1.9 to 14% CO_2 (NNP −42 to 314 g/kg $CaCO_3$), although six samples (7, 8, 15, 16, 19, and 34) showed negative mineral NNP values while their corresponding analytical results are positive (Fig. 3).

Paste pH

Of the 20 samples, four (composites 7, 8, 26, and 27) showed acidity (paste pH < 6; Table 7). However, not all samples from the acidic, slightly acidic, inert/neutral, and slightly basic types produced acidity.

Net Acid Generation pH

The pH of five of the 20 composite samples (composite 26, 27, 30, 31, and 34) decreased below 4.5, indicating net PAG (Table 7). These samples were from the acidic, slightly acidic, and basic types.

Table 5 X-ray diffraction and mineral liberation results for the Genesis samples

ID	1	4	10	3	21	34	6	8	23	5	7	11	15	16	19	20	27	31	26	30
NCV type	Highly basic			Basic			Slightly basic			Inert/neutral							Slightly acidic		Acidic	
XRD																				
Quartz	13	16	49	10	54	26	55	64	57	61	55	55	66	71	80	70	30	63	57	55
K-feldspar		7		9	15	25						9			8		22	13		16
Plagioclase				18		6														
Amphibole						2														
Diopside	27	26	5	24	9	10						7						4		
Garnet																				
Illite	25	9	12	27	9	12	20	15	20	15	10		15	9		14		9		5
Kaolinite	4	5	18		6		18	15	21	22	33	27	18	18	10	12	45	9	34	17
Smectite																				
Chloride						7														
Siderite	3					9														1
Rhodochrosite					5															
Alunite																			5	
Jarosite					1	1									2	2	2		1	3
Barite												1								
Apatite																				
Iron oxide	1	1		5			7	6	2	2	2	1	1	2		2				
Calcite	13	35	16	6								Tr.								
Dolomite	14																			
Pyrite		1		1	1	2											1	2	3	3
MLA																				
Pyrite	0.12				0.71	2.7	0.01	0.08		0.01	0.09		0.01	<0.01	0.03	0.1	0.44	0.87	0.821	1.37
Pyrite-As-rich	0.02									<0.01		<0.01	0.01	0.01	0.02	0.06	0.25	0.47	1.32	0.7
Calcite	1.0				0.03	0.01	0.01		0.05	0.02	0.01	0.02	<0.01		0.01	0.06		0.03	0.01	<0.01
Dolomite	27.4				1.9	2.7	0.01	d	0.07	0.03	0.01	0.01	0.01	<0.01	0.03	0.06	0.01	0.03	<0.01	0.01
Siderite-Mg-rich					3.9	6.1		0.03												
Alunite					0.01	0.02	0.05	0.01	<0.01	0.01	d	0.2		<0.01	0.01	0.01	0.2	0.03	1.9	<0.01
Jarosite							0.01		<0.01	0.05			0.02		0.09	0.1	0.58	0.04	0.12	<0.01
Barite					0.01	0.01		0.02		0.01	0.01	0.03				0.02		0.01	0.25	0.01

Table 6 Mineral acid-generating/neutralizing potential results for Genesis samples

ID	NCV type	Calcite (%)	Dolomite (%)	Carbonate (% C)	NP (% CO_2)	NP (g/kg $CaCO_3$)	Pyrite (%)	Sulfide (% S)	AP (% CO_2)	AP (g/kg $CaCO_3$)	NCV (% CO_2)	NNP (g/kg $CaCO_3$)	NP/AP	NP/ AP*	BLM criteria	NDEP criteria
1	Highly basic	13*	14*	3.4	12.4	281.6	0.1	0.07	0.1	2.3	12.3	279.3	122.0	122.0	Non acid	Non acid
3	Basic	6*	0*	0.7	2.6	60.0	1*	0.5	0.7	16.6	2.6	60.0	132.1	132.1	Non acid	Non acid
4	Highly basic	35*	0*	4.2	15.4	349.9	1*	0.5	0.7	16.6	15.4	349.9	770.7	770.7	Non acid	Non acid
5	Inert/neutral	0.02	0.03	0.01	0.02	0.5	0.02	0.01	0.01	0.2	0.01	0.3	2.1	2.1	Uncertain	Non acid
6	Inert/neutral	0.01	0.01	0.00	0.01	0.2	0.01	0.01	0.01	0.2	0.00	0.0	1.3	1.3	Uncertain	Non acid
7	Inert/neutral	0.01	0.01	0.00	0.01	0.2	0.09	0.05	0.07	1.5	−0.06	−1.3	0.1	0.1	Uncertain	Uncertain
8	Inert/neutral	0	0	0.00	0.00	0.00	0.08	0.04	0.06	1.3	−0.06	−1.3	0.0	0.0	Uncertain	Uncertain
10	Highly basic	16*	0*	1.9	7.0	160.0	0*	0.00	0.00	0.00	7.0	160.0	No AP	352.3	Non acid	Non acid
11	Inert/neutral	0.02	0.01	0.00	0.01	0.3	0.01	0.00	0.00	0.08	0.01	0.2	No AP	3.7	Uncertain	Non acid
15	Inert/neutral	0.005	0.01	0.00	0.01	0.2	0.02	0.01	0.01	0.3	−0.01	−0.2	0.5	0.5	Uncertain	Uncertain
16	Inert/neutral	0	0.01	0.00	0.00	0.05	0.02	0.01	0.01	0.2	−0.01	−0.2	0.2	0.2	Uncertain	Uncertain
19	Inert/neutral	0.01	0.03	0.01	0.02	0.4	0.05	0.03	0.04	0.8	−0.02	−0.4	0.5	0.5	Uncertain	Uncertain
20	Inert/neutral	0.06	0.06	0.02	0.06	1.2	0.2	0.08	0.1	2.6	−0.06	−1.4	0.5	0.5	Uncertain	Uncertain
21	Slightly basic	0.03	1.92	0.3	0.9	21.1	0.7	0.4	0.5	11.7	0.4	9.4	1.8	1.8	Uncertain	Non acid
23	Inert/neutral	0.05	0.07	0.02	0.06	1.3	0.00	0.00	0.00	0.00	0.06	1.3	No AP	2.8	Uncertain	Non acid
26	Acidic	0.01	0.01	0.00	0.01	0.2	2.1	1.1	1.6	35.3	−1.5	−35.1	0.0	0.0	Uncertain	Uncertain
27	Slightly acidic	0	0.01	0.00	0.00	0.1	0.7	0.37	0.5	11.4	−0.5	−11.3	0.0	0.0	Uncertain	Uncertain
30	Acidic	0.005	0.01	0.00	0.01	0.2	2.1	1.1	1.5	34.1	−1.5	−34.0	0.0	0.0	Uncertain	Uncertain
31	Slightly acidic	0.03	0.03	0.01	0.03	0.6	1.3	0.7	1.0	22.1	−0.9	−21.5	0.0	0.0	Uncertain	Uncertain
34	Slightly acidic	0.01	2.67	0.3	1.3	29.0	2.7	1.4	2.0	44.5	−0.7	−15.5	0.7	0.7	Uncertain	Uncertain

NP acid-neutralizing potential, *AP* acid-generating potential, *NCV* net carbonate value, *NNP* net neutralization potential. Pyrite, calcite, and dolomite percentages are determined from MLA analysis, except for * using XRD. BLM criteria for acid-neutralizing potential is NNP > 20 g/kg $CaCO_3$ and NP/AP > 3. NDEP criteria for acid-neutralizing potential is NP/AP > 1.2. Negative NP and positive AP are corrected to zero before NCV calculation. NP/AP* are calculated using detection limit value

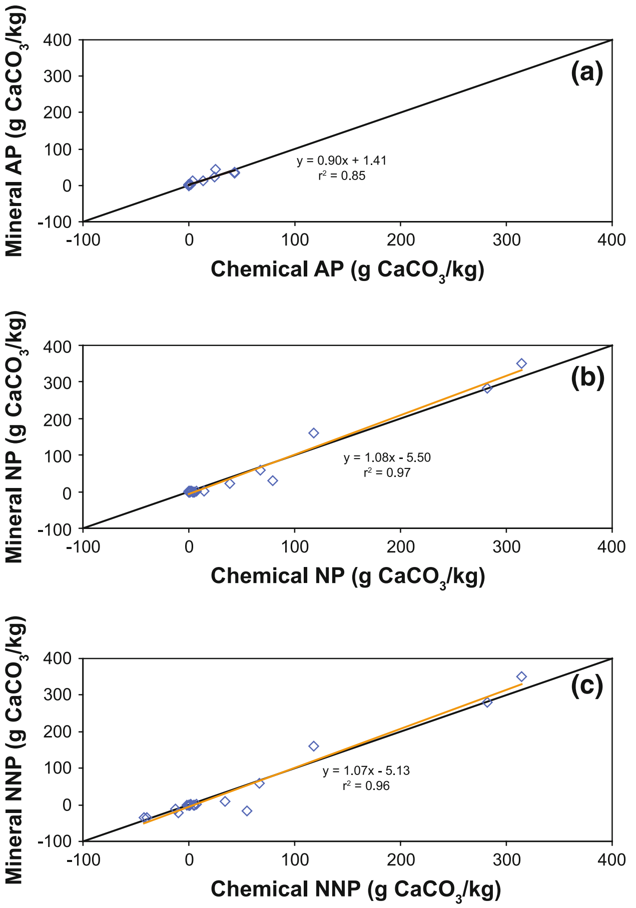

Fig. 3 Correlation of **a** acid-generating potential (AP), **b** acid-neutralizing potential (NP), and **c** net neutralization potential (NNP) using the chemical and mineralogical data

Humidity Cells

Four methods were developed to assess the PAG of HCTs: (1) the evolution of net alkalinity (in conjunction with the leachate pH), which provides an indication of the available carbonate buffering capacity remnant in the sample; (2) the relative mass release of carbonate dissolution (Ca + Mg release) compared to sulfide oxidation (sulfate release) to define the remaining acid neutralization capacity; (3) a comparison of cumulative rates of carbonate dissolution versus sulfide oxidation to determine the remnant mass of carbonate and sulfide in the HCT at the conclusion of the test; and (4) the prediction of future carbonate dissolution and sulfide oxidation to estimate which mineral is dissolving faster.

Evolution of Net Alkalinity and Leachate pH

The leachate pH of all four composite samples from the acidic and slightly acidic categories generated acid (pH 2.1 to 5.3; Fig. 4), consistent with the negative NCV values. One of the seven inert/neutral samples (composite 7) released net acidity during the tests (Table 7), with pH decreasing from 6 to 4.5 over 20 weeks. Six of the seven inert/neutral samples exhibited neutral to slightly basic pH and released net alkalinity during the 20 week period. For the slightly basic materials, one of the three samples (composite 8) released net acidity, with pH values ranging from 3.6 to 4.3. For the basic materials, two of the three samples (composites 21 and 34) showed low pH at the beginning of the tests, probably due to dissolution of soluble acid sulfates, while all of the basic samples released net alkalinity over the 20 week period. None of the three highly basic samples released net acidity, with the pH ranging from 6.6 to 8.4, consistent with the positive NCV values. Based on these data, the propensity of the inert/neutral and slightly basic codes to generate long-term acidity is uncertain and mandates additional interpretation to reach a conclusion.

Relative Mass Release of Carbonate Dissolution Compared to Pyrite Oxidation

The molar ratio of (Ca + Mg/sulfate) was also used to estimate the balance between acid-generating and acid-neutralizing rates by comparing the net solution acidity with the alkalinity engendered from calcite and dolomite, i.e.:

$$FeS_2 + 3.25O_2 + 3.5H_2O \rightarrow Fe(OH)_3 + 2SO_4{}^{2-} + 4H^+ \tag{12}$$

$$CaCO_3 + 2H^+ \rightarrow Ca^{2+} + H_2O + CO_{2(g)} \tag{13}$$

$$CaMg(CO_3)_2 + 4H^+ \rightarrow Ca^{2+} + Mg^{2+} + H_2O + CO_{2(g)} \tag{14}$$

Based on Eqs. 12 through 14, two moles of calcite or one mole of dolomite are required to neutralize 4 mol of protons, assuming that the bulk of Ca and Mg are derived from carbonate dissolution while sulfate is generated from pyrite oxidation. This is a reasonable assumption because the dissolution kinetics of Ca- and Mg-bearing minerals (e.g. feldspar silicates and clays) are much slower than for carbonates (Lengke and Tempel 2005). Therefore, a molar ratio of $[(Ca + Mg)/sulfate)] > 2$ or $[(Ca + Mg)/sulfate)] > 1$ should be observed if calcite or dolomite, respectively, is neutralizing pyrite-derived acidity (Eqs. 12 and 14). Four of the six acid-generating samples had a ratio of $[(Ca + Mg)/sulfate)] < 1$ while two (7 and 8) were both 1.3 (however, neither contained dolomite). The twelve non-acid-generating samples had a ratio of $[(Ca + Mg)/sulfate)] > 2$ (Table 8). Composites 21 and 34 contained mostly dolomite (1.9 and 2.7%, respectively; Table 5) and little calcite (0.03 and 0.01%, respectively; Table 5), and

Table 7 Net acid generation pH, paste pH, and humidity cell results for Genesis samples

ID	Chemical NNP (g/kg $CaCO_3$)	Mineral NNP (g/kg $CaCO_3$)	NAG pH	Paste pH	Humidity cells					Forecast from humidity cells	
					Net alkalinity (mg/kg $CaCO_3$)	Final pH	Ca + Mg/SO_4	Pyrite rate (mg/kg $CaCO_3$)	Carbonate rate (mg/kg $CaCO_3$)	Lifetime of pyrite[a] (years)	Lifetime of carbonate[a] (years)
1	281.7	279.3	8.42	8.84	801.6	7.11	4.9	*	784	*	184.8
3	66.8	60.0	10.02	8.57	576.9	7.55	2.0	495	667	1.3	54.8
4	314.4	349.9	7.93	8.63	786.3	7.98	4.8	*	664	*	355.8
5	1.5	0.3	6.94	7.51	501.3	7.94	7.7	*	389	*	1.9
6	5.8	0.0	7.44	7.28	692.5	7.46	13.6	*	468	*	5.7
7	1.3	−1.3	4.67	5.66	−85.6	4.45	1.3	697	925		
8	4.7	−1.3	4.81	5.3	−129.6	3.79	1.3	648	494		
10	118.5	160.0	7.88	8.07	743.8	7.61	12.0	*	548	*	101.7
11	1.1	0.2	6.49	6.8	219.2	7.74	2.4	*	935	*	0.8
15	0.2	−0.2	6	7.43	487.5	7.59	15.5	*	*	*	*
16	0.0	−0.2	5.54	7.04	185.3	7.70	2.4	*	*	*	*
19	1.2	−0.4	4.89	7.01	146.3	7.84	2.9	190	233	5.7E + 148	1.1
20	−1.6	−1.4	5.34	6.99	333.3	7.83	3.8	363	*	3.3E + 117	*
21	34.6	9.4	5.75	7.2	179.2	7.02	1.2	2142	2087	3.4E + 19	5.3E + 30
23	7.2	1.3	7.67	7.47	707.2	7.22	8.8	*	347	*	10.5
26	−42.1	−35.1	2.44	4.11	−11648.9	2.24	0.2	14659	2600		
27	−12.4	−11.3	3.25	4.68	−803.2	2.81	0.7	4478	3003		
30	−39.6	−34.0	2.42	6.1	−3361.6	2.33	0.5	10032	4849		
31	−10.0	−21.5	2.89	6.8	−1009.5	2.62	0.6	6641	4263		
34	54.7	−15.5	3.32	6.99	181.3	6.66	0.9	4459	3929	3.7E + 24	7.0E + 26

* Sulfide and carbonate content were below detection limit values

[a] Lifetimes of pyrite and carbonate were calculated using total sulfur and carbonate from the net carbonate value (NCV) method

the computed ratios for 21 (1.2) and 34 (0.9) are in good agreement with this hypothesis.

Comparison of Cumulative Rates of Carbonate Dissolution Versus Sulfide Oxidation

The HCT data also allow estimates of mineral reaction rates. The carbonate dissolution rate was calculated using the mass release of Ca and Mg, with the assumption that all Ca and Mg was derived from carbonate. Gypsum and anhydrite were absent based on XRD and MLA while geochemical modeling confirmed that all HCT effluents were undersaturated with respect to these phases. Therefore, the carbonate dissolution rate was estimated using the mass release of Ca and Mg.

The pyrite oxidation rate was calculated using the mass release of sulfate, assuming all was generated by pyrite oxidation. Sulfate rather than Fe was used in the pyrite oxidation calculation because iron oxide, which would confound the calculations, was identified by both XRD and MLA. However, based on the XRD and MLA results, small fractions of barite, jarosite, and alunite were initially present as other potential sources of sulfate (Table 5). The geochemical modeling results indicate that jarosite is unlikely to precipitate, but alunite may precipitate over the course of the HCTs (e.g. composite 7). Therefore, the pyrite oxidation rate calculated from sulfate probably represents an overestimate but is consistent with the tenets of the “Precautionary Principle,” in that risk will not be underestimated.

If the carbonate dissolution rate is equal to or greater than the pyrite oxidation rates, then the samples should not generate acid until all carbonate is depleted (e.g., Fig. 5a). Over the 20 week period, five of the six PAG samples (8, 26, 27, 30, and 31) had a pyrite oxidation rate greater than the carbonate dissolution rate (e.g., Fig. 5b) while in 7, sulfate may have been lost from solution due to the precipitation of alunite. In 11 of the 14 non-PAG composites (1, 3, 4, 5, 6, 10, 11, 15, 16, 19, and 23), the pyrite oxidation rate was lower than the carbonate dissolution rate (Table 7). The others (20, 21 and 34) exhibited the converse, due either to a high sulfate release generated from a secondary source of alunite and barite dissolution in addition to pyrite oxidation, or low Ca and Mg release, due to slow dolomite dissolution.

Fig. 4 Variation in Genesis humidity cell pH with time for **a** highly basic, **b** basic, **c** slightly basic, **d** inert/neutral, **e** slightly acidic, and **f** acidic net carbonate value (NCV) type

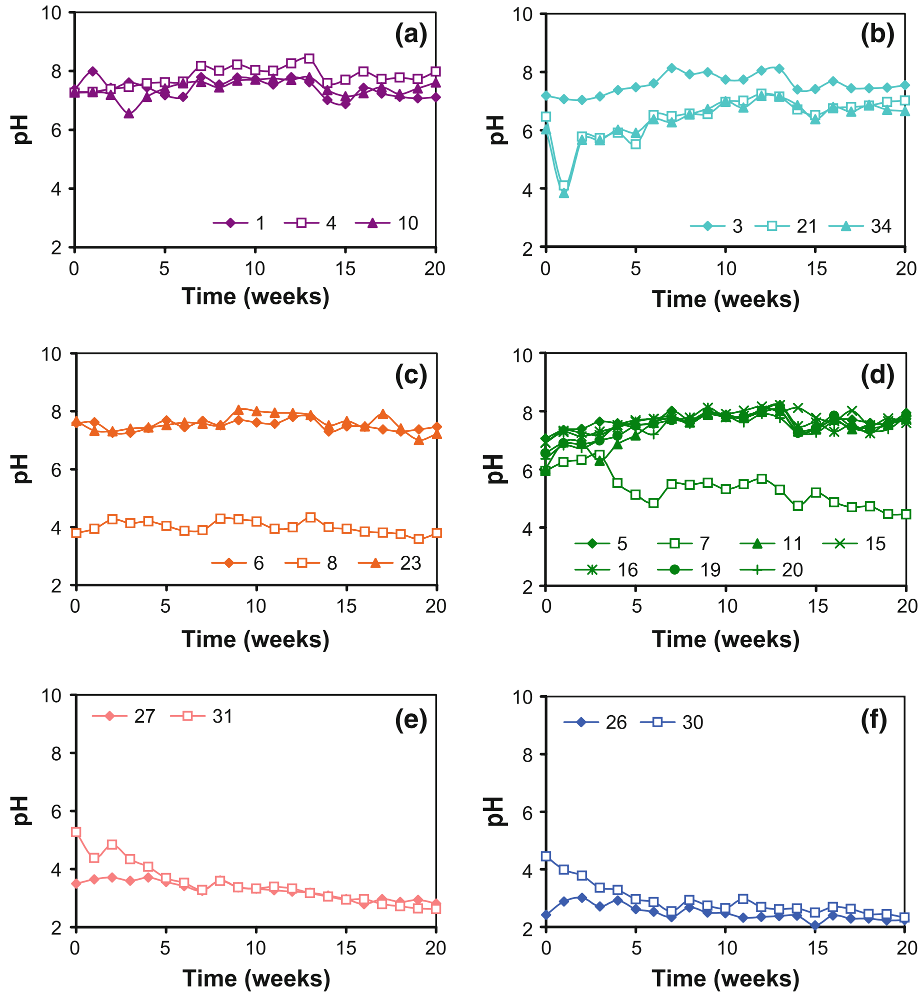

Table 8 Best-fitted lines of the cumulative percentage of carbonate dissolution and pyrite oxidation with time

ID	Pyrite	R^2	Carbonate	R^2
1			$y = 0.01x + 0.07$	0.98
3	$y = 0.0007x^3 - 0.03x^2 + 0.4x + 0.5$	0.99	$y = 0.04x + 0.2$	0.99
4			$y = 0.005x + 0.1$	0.99
5			$y = 0.9x + 6.1$	1.00
6			$y = 0.3x + 1.1$	1.00
10			$y = 0.02x + 0.06$	1.00
11			$y = 16.4\mathrm{Ln}(x) + 38.5$	0.93
19	$y = 0.3\mathrm{Ln}(x) + 1.0$	0.97	$y = 0.001x^3 - 0.05x^2 + 0.8x + 3.3$	0.99
20	$y = 0.4\mathrm{Ln}(x) + 1.4$	0.93		
21	$y = 2.0\mathrm{Ln}(x) + 1.6$	0.97	$y = 1.3\mathrm{Ln}(x) + 1.5$	0.99
23			$y = 0.2x + 1.0$	1.00
34	$y = 1.7\mathrm{Ln}(x) - 0.04$	0.98	$y = 1.5\mathrm{Ln}(x) + 0.2$	0.99

Predicting Future Carbonate Dissolution and Sulfide Oxidation

To estimate future carbonate dissolution and pyrite oxidation rates beyond the 20 week duration of the HCTs, best-fit lines were derived from the cumulative percentage of carbonate dissolution and pyrite oxidation with time (Table 8; Fig. 6). The total sulfur and carbonate contents from the NCV method were used in the calculations, assuming that the respective carbonate dissolution and

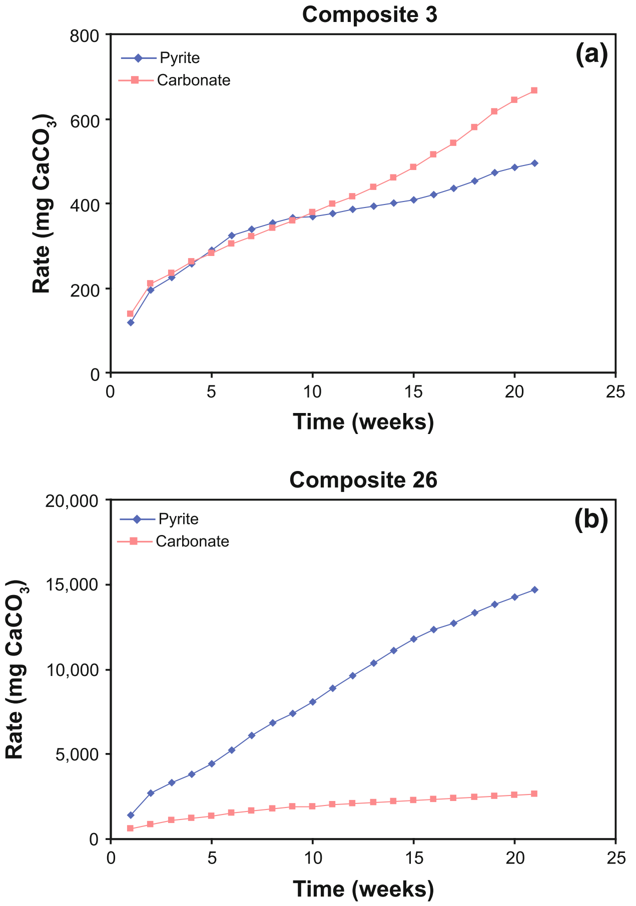

Fig. 5 An example of estimation of carbonate dissolution and pyrite oxidation in **a** composite 3 and **b** composite 26

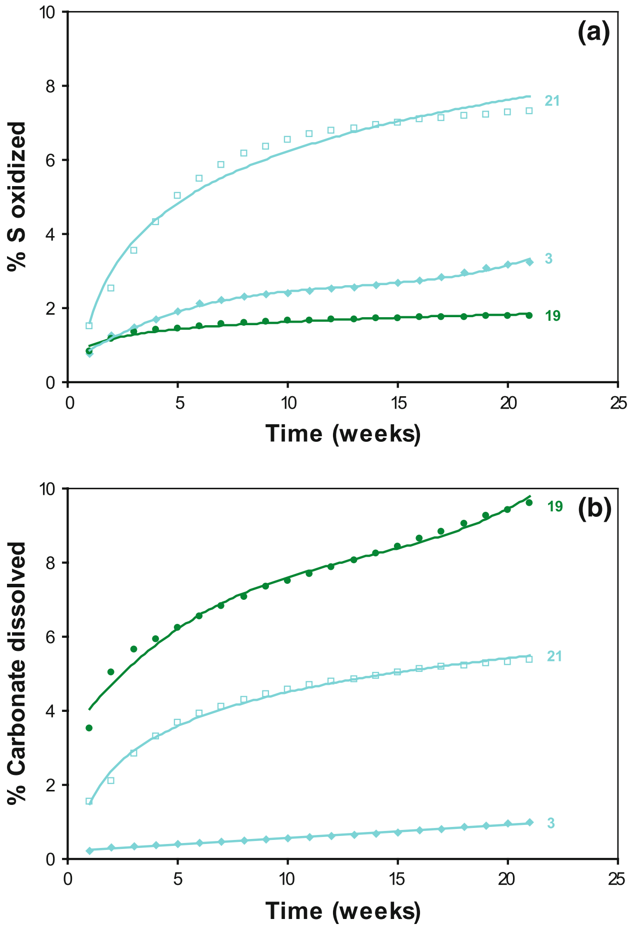

Fig. 6 Cumulative of dissolution/oxidation rates of **a** pyrite and **b** carbonate for composites 3. 19 and 21

pyrite oxidation rates would be similar after 20 weeks and that mineral precipitation is limited. This approach is useful to evaluate PAG for samples that have not yet released acidity over the 20 week period (i.e., composites 1, 3, 4, 5, 6 10, 11, 19, 20, 21, 23, and 34). The results show that carbonate minerals will remain after all sulfide has dissolved in composites 1, 3, 4, 5, 6, 10, 11, 21, 23, and 34. For 2 samples (19 and 20), remnant pyrite is predicted after the carbonate minerals have been depleted (Table 7).

In summary, the HCTs show that 6 of 20 samples (7, 8, 26, 27, 30, and 31) are unambiguous in their acid production tendencies. Twelve of the remaining 14 samples will not generate acidity because carbonate will remain after their pyrite content has been exhausted (Table 7). The other two samples, 19 and 20, although remaining neutral over the course of the HCTs, contain sufficient sulfide based on the chemical and mineralogical results (Tables 3, 6) to represent PAG. This analysis is conservative because the effects of feldspar silicate neutralization and sulfide encapsulation have not been incorporated in this analysis.

Discussion

From the perspective of waste rock management during active mining operation, conducting HCTs for many years to identify the appropriate placement of waste rock is ineffective because such decisions must be made on a real-time basis. Nevertheless, if units with an uncertain PAG character will not be mined until many years into the life-of-mine, a contingency plan (CP) may be warranted to collect kinetic data on an ongoing basis as mining progresses to provide greater surety as to appropriate waste rock placement of these materials. This is a mine-specific issue that requires analysis on the basis of such criteria as presented in this study.

As a precursor to the onset of mining at Genesis, a combination of static analytical test results, including NNP, paste pH, and NAG pH, was used to develop a screening tool to estimate acid-generating potential. The predictive results from these methods were compared to total of 20 week HCTs and/or the post-HCT forecast of acid-generating potential. HCT results were selected because they

Table 9 Summary of acid-generating testing results for the Genesis composite samples; if any of the tests indicate acid, then the sample was classified as acid

ID	Chemical NNP		Mineral NNP		NAG pH	Paste pH	Summary of static tests	Humidity cells (20 weeks)				Forecast from humidity cells	Summary of kinetic tests
	BLM criteria	NDEP criteria	BLM criteria	NDEP criteria				Net alkalinity	Final pH	Ca + Mg/SO_4	Pyrite vs. carbonate rates		
1	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid
3	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid
4	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid
5	Uncertain	Non acid	Uncertain	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid
6	Uncertain	Non acid	Uncertain	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid
7	Uncertain	Non acid	Uncertain	Uncertain	Non acid	Acid	Acid	Acid	Acid	Acid	Non acid		Acid
8	Uncertain	Non acid	Uncertain	Uncertain	Non acid	Acid	Acid	Acid	Acid	Acid	Acid		Acid
10	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid
11	Uncertain	Non acid	Uncertain	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid
15	Uncertain	Uncertain	Uncertain	Uncertain	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid
16	Uncertain	Uncertain	Uncertain	Uncertain	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid
19	Uncertain	Non acid	Uncertain	Uncertain	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Uncertain	Uncertain	Uncertain
20	Uncertain	Uncertain	Uncertain	Uncertain	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Uncertain	Uncertain	Uncertain
21	Non acid	Non acid	Uncertain	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid
23	Uncertain	Non acid	Uncertain	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid	Non acid
26	Uncertain	Uncertain	Uncertain	Uncertain	Acid	Acid	Acid	Acid	Acid	Acid	Acid		Acid
27	Uncertain	Uncertain	Uncertain	Uncertain	Acid	Acid	Acid	Acid	Acid	Acid	Acid		Acid
30	Uncertain	Uncertain	Uncertain	Uncertain	Acid	Acid	Acid	Acid	Acid	Acid	Acid		Acid
31	Uncertain	Uncertain	Uncertain	Uncertain	Acid	Acid	Acid	Acid	Acid	Acid	Acid		Acid
34	Non acid	Non acid	Uncertain	Uncertain	Acid	Non acid	Acid	Non acid	Non acid	Uncertain	Non acid	Non acid	Non acid

reflect (a) conservative conditions, and (b) longer-term potential of fully oxygenated samples to generate or consume acidity.

For samples in the alkaline or acidic range of the spectrum, the NMC standard NCV classification is an accurate determinator, e.g. for NNP ≤ -2.27 g/kg $CaCO_3$ (acidic and slightly acidic) and NNP > 22.7 g/kg $CaCO_3$ (basic and highly basic). All four acidic and slightly acidic samples released acid in the HCTs. The NNP, paste pH, NAG pH, and the HCT results also indicate that highly basic and basic samples were not PAG, except for composite 34, the only one with a NAG pH < 4.5 (Table 7), probably due to siderite (6%).

From a management perspective, the challenge to accurately portray the PAG nature of waste rock lies in accurate classification of the intermediate codes over the range of NNP > -2.27 to NNP < 22.7 g/kg $CaCO_3$ (inert/neutral and slightly basic). This material represents half (54%) of the Genesis waste rock (240 million tonnes out of a projected total 440 million tonnes). These materials were characterized by 10 HCTs (Fig. 4), of which two (7 and 8) released net acidity during the 20 week HCT period. This behavior is the basis for a CP to allow ongoing analysis of waste material prior to encountering it in the mine sequence.

Several methods were developed in this study to provide insight as to the PAG character of waste rock. On a cumulative basis (Table 9), six (7, 8, 26, 27, 30 and 31) were clearly acidic, 12 were clearly non acid-generating (1, 3, 4, 5, 6, 10, 11, 15, 16, 21, 22, 34), and two (19 and 20) remain uncertain.

Another element of this analysis relates to the appropriate duration of HCTs. Based on this data set, six became acidic after 20 weeks while 12 are demonstrably non-acid generating after combining the multiple test results (analytical and computed). Two samples (19 and 20) potentially require ongoing analysis beyond 20 weeks to clarify any PAG tendency based on sulfide availability computations. The materials represented by these samples are candidates for further analysis under a CP.

Conclusions

Correct decisions on managing mining waste materials, sending them either into an engineered waste material facility in the event that the materials are PAG, or backfilled into pits or sent to standard waste rock facilities if not PAG is required both to meet permit requirements and as part of ongoing good stewardship practices. Several combinations of test protocols to refine the predictive accuracy of the NCV or NNP-only predictor were evaluated in this study, including NNP, paste pH, and NAG pH. The static test results were compared to the 20 week HCT data, including net alkalinity, pH, a molar ratio of (Ca + Mg/sulfate), and cumulative rates of carbonate dissolution and pyrite oxidation and/or the post HCT forecast. In summary, the static results indicated that 7 of 20 composites (7, 8, 26, 27, 30, 31 and 34) are PAG while the kinetic test results over the 20 weeks show 6 of 20 composites (7, 8, 26, 27, 30 and 31) released acidity. For the remaining 14 samples that did not release acidity over the 20 weeks HCT duration, two samples (composite 19 and 20) remained uncertain, although most static tests indicate non-PAG materials. The materials represented by these tests are candidates for additional analysis under a CP. On this basis, only these two HCTs should have been run longer; adequate information is available for the other codes to allow robust field decisions to be made regarding waste rock disposition.

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References

Akabzaa TM, Armah TEK, Baneong-Yakubo BK (2007) Prediction of acid mine drainage generation potential in selected mines in the Ashanti metallogenic belt using static geochemical methods. Environ Geol 52:957–964

Allison JD, Brown DS, Novo-Gradac KH (1991) MINTEQA2—a geochemical assessment model for environmental systems. US Environmental Protection Agency Environmental Research Laboratory, Center for Exposure Assessment Modeling, EPA/6003-91/021, Athens, GA, 92 pp

American Society for Testing and Materials (1996) Standard test method for accelerated weathering of solid materials using a modified humidity cell. ASTM D 5744-96, West Conshohocken, PA, USA, 13 pp

American Society for Testing and Materials (2007a) Standard test method for accelerated weathering of solid materials using a modified humidity cell. ASTM D 5744-07, West Conshohocken, PA, USA, 19 pp

American Society for Testing and Materials (2007b) Standard test methods for analysis of metal bearing ores and related materials by combustion infrared-absorption spectrometry. ASTM E 1915-07, West Conshohocken, PA, USA, 14 pp

BLM (1996) Instruction memorandum 96–79. April 2. US Bureau of Land Management, Washington, DC, USA, 6 pp

Brodie MJ, Broughton LM, Robertson AM (1991) A conceptual rock classification system for waste management and a laboratory method for ARD prediction from rock piles. Proceedings of 2nd International Conference on the Abatement of Acidic Drainage, Montreal, Canada, Tome 3, pp 119–135

Day SJ (1989) Comments after presentation of "A practical approach to testing for acid mine drainage in the mine planning and approval process". 13th Annual British Columbia Mine Reclamation Symp, Vernon, BC, Canada

Ferguson KD, Morin KA (1991) The prediction of acid rock drainage—lessons from the database. Proceedings of 2nd

International Conference on the Abatement of Acidic Drainage, Montreal, Canada, Tome 3, p 83–106

Lengke MF, Tempel RN (2005) Geochemical modeling of arsenic sulfide oxidation kinetics in a mining environment. Geochim Cosmo Acta 69:341–356

Miller SD (1998) Predicting acid drainage. Australian minerals and energy environment foundation groundwork. 2:8–9

Morin KA, Hutt NM (1994) Observed preferential depletion of neutralization potential over sulfide minerals in kinetic tests—site specific criteria for safe NP/AP ratios. Proceedings of International Land Reclamation and Mine Drainage Conference on the Abatement of Acidic Drainage, US Bureau of Mines SP 06A-94, Pittsburgh, PA, USA, pp 148–156

NDEP (1990) Waste rock and overburden evaluation version 1.4.94 (Sept 14, 1990). Nevada Div of Environmental Protection, Bureau of Mining Regulation and Reclamation, Carson City, NV, USA, 2 pp

Nordstrom DK, Alpers CN (1999) Geochemistry of acid mine waters. In: Plumlee GS, Logsdon MJ (eds) The environmental geochemistry of mineral deposits, Part A: processes, techniques, and health issues, vol 6A. Rev Econ Geol, pp 133–160

Parkhurst DL, Appelo CAJ (1999) User's guide to PHREEQC (version 2)—a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical modeling. US Geological Survey WRI Report 99-4259, Denver, CO, USA, 310 pp

Plumlee GS (1999) The environmental geology of mineral deposits. In: Plumlee GS, Logsdon MJ (eds) The environmental geochemistry of mineral deposits, Part A: processes, techniques, and health issues, vol 6A. Rev Econ Geol, pp 71–116

Sobek AA, Schuller WA, Freeman JR, Smith RM (1978) Field and laboratory methods applicable to overburden and minesoils. US Environmental Protection Agency Report EPA-600/2-78-054, 203 pp

US Environmental Protection Agency (1994) Acid mine drainage prediction. EPA-530-R-94-036, Washington, DC, USA, 48 pp

US Environmental Protection Agency (2009) Method 1627: kinetic test method for the prediction of mine drainage quality. EPA-530-R-94-056, Washington, DC, USA, 40 pp

White WW III, Lapakko KA, Cox RL (1999) Static-test methods most commonly used to predict acid-mine drainage. In: Plumlee GS, Logsdon MJ (eds) The environmental geochemistry of mineral deposits, Part A: processes, techniques, and health issues, vol 6A. Rev Econ Geol, pp 325–338