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ORIGINAL ARTICLE

Prediction of acid mine drainage generation potential in selected mines in the Ashanti Metallogenic Belt using static geochemical methods

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Abstract Acid mine/rock drainage (AMD/ARD) is the biggest environmental threat facing the mining industry. This study investigates AMD/ARD possibilities in three mines in the Ashanti Belt, using acid base accounting (ABA) and net acid generation pH (NAGpH) tests. Twenty-eight samples of rock units and mine spoil from these mines were collected for ABA and NAGpH tests. Two tailing dumps at Prestea and Nsuta were confirmed by both methods as acid generating with NAGpH of 4.5 and 4.6 and neutralization potential ratio values of 4.38 and 4.60, respectively. Six other samples are classified as potentially acid generating using a variety of established classification criteria. The rest of the samples either exhibited very low sulphur and carbonate content or had excess carbonate over sulphur. Consistency between results from ABA and NAGpH tests validates these tests as adequate tools for preliminary evaluation of AMD/ARD possibilities in any mining project in the Ashanti Belt.

Keywords Acid mine drainage · Prediction · Ashanti Belt

Introduction

Mineral extraction and the waste generated from mine sites and their impacts on human health and the environment is noted to be a serious and continuing problem facing industry, government agencies and the public globally (Durkin and Hermann 1994; King 1995). Among all the aspects of mining that impact negatively on the environment, the phenomenon of acid rock and/or mine drainage (ARD/AMD) and the heavy metal contamination associated with it is widely regarded as the most intense and persistent mining related environmental problem (Da Rosa and Lyon 1997). It is a source of surface and ground water pollution and where it has occurred has resulted in serious ecological disasters (Schreck 1998; Taylor 1998).

Acid rock/mine drainage (ARD/AMD) is a naturally occurring process produced from the oxidation of sulphur to sulphates and leading to the production of acidity, sulphate and iron whenever water containing oxygen comes into contact with sulphur present as sulphides in mineralized rock and mine wastes (Nriagu 1978; Smith and Skema 2001). The process is usually accelerated when mining exposes metal sulphides in rocks to oxygen and water, allowing rapid oxidation of the sulphides and dissolution of their products, which usually include potentially toxic heavy metals. The transport of such oxidation products culminates in drainage waters with anomalous loading of dissolved elements that reflect the mineral composition of the drained rocks. Jones (1998) pointed out that the pH of such drainage and the concentrations of metals are a function of the balance between acid generating and acid neutralizing minerals and their elemental composition and are site specific.

It is now understood that a thorough understanding of both local and regional geochemical processes can lead to a better understanding of environmental impacts of acid drainage and the associated metal leaching. Such an understanding is critical for the

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development of acid drainage prediction and treatment strategies and for the evolution of environmental guidelines acid drainage and metal leaching management.

Unfortunately, the growing efforts to understand the phenomenon of acid drainage and its menace and the growing literature on it have been disproportionately confined to the developed countries. The subject is a gray area in most mining centres in Africa in particular. Ghana, despite been a major player in the mining industry, with a long history of mining, does not have an elaborate framework for acid drainage management.

Most active and historic mines in the country are situated within the Birimian and Tarkwaian rock systems. It is generally acknowledged that sulphide mineralization is pervasive in these Proterozoic rocks, especially the Birimian meta sediments and meta volcanics, with possibilities for acid mine drainage generation. Unfortunately, very few companies give ARD evaluation a serious attention during the Environmental Impact Assessment (EIA) studies. The assertion is that the rocks contain sufficient carbonate alterations to provide sufficient buffering to any available acid generating material (Anonymous 1994, 1996, 1998). In a few exceptional cases for which ARD evaluation has be done in Ghana, the companies have been criticized for using unconventional in-house non-conventional acid base accounting procedures without complementary tests (Anonymous 2005).

Empirical medical records from the Tarkwa mining district of southwestern Ghana suggest that reported cases of acute skin diseases and mental disorders are on the increase. Heavy metals such as arsenic, manganese and mercury, typical products of acid drainage, have long been known to be the sources carcinogenic, dermatitis or neurological disorders (Smedley and Kinniburgh 2002; Jamieson and Pryzbylowicz 1997; Songsore et al. 1994). In fact, health surveillance and related research in the area has showed that arsenic dermatitis is common in some communities within the periphery of some mines in the area (Songsore et al. 1994; Akabzaa 2000).

These findings underscore the need for further investigation into the distribution and concentration and sources of these contaminants in the area. As observed by Bell et al. (2002) elevated metal leaching, such as those mentioned above is usually associated with acid drainage due to high metal solubility and sulphide weathering rates under acidic conditions. This study therefore assesses the potential of the various lithological units likely to be affected by mining in the Prestea, Tarkwa and Nsuta mines to generate acid drainage, using static geochemical acid drainage predictive methods.

A number of static and kinetic geochemical testing methods for acid drainage prediction have evolved over the years. However, as Filipek et al. (1999) and Schafer (2000) acknowledged, because of the complexity of the physical, chemical and biological processes involved in producing and neutralizing ARD, no individual of these methods alone has proven completely accurate, and a combination of static and kinetic methods is usually relied upon to increase prediction accuracy.

It is equally been acknowledged that acid base accounting (ABA) remains the static method of choice for evaluating the acid drainage potential of a test sample (Kwong 2000) and that ABA in combination with NAGpH tests is adequate for screening samples for their acid generation potential (Schafer 2000; Greenhill 2000; Canadian Mine Environment Neutral Drainage (MEND) 2001. Routinely, kinetic humidity cell tests have been used to assess the ARD potential of samples to confirm results of ABA tests. However, this method is time and financial resource consuming. Recent works have however shown that NAGpH test results have been comparable to kinetic humity cells at a variety of mines. The NAGpH test has been described as a very simple, rapid and cost effective method that combines features of static and kinetic tests. The method stimulates a long period of oxidation in 24 h (Schafer 2000; Greenhill 2000).

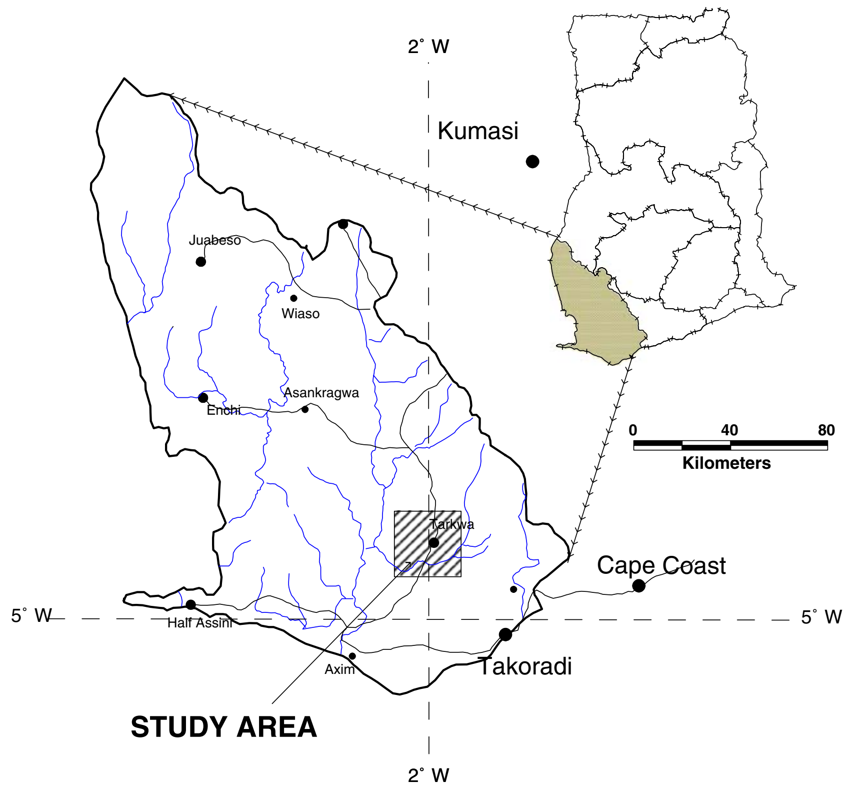
Thus, in this assessment, ABA and NAGpH tests are employed to investigate the study site for the acid generation potential of the various lithological units and mine spoil. These methods, like any other methods, are not intended to predict the rate of acid generation, but the potential to produce acid are considered adequate screening tests for the acid generation potential of any site.

Study area

The area is within the Wassa west district of the western region (Fig. 1). Annual rainfall and temperature in the area average about 1,874 mm and 26°C, respectively. The area is part of the extensive Ankobra River Basin and its mosaic of tributaries that collectively receive mine-impacted drainage from both large-scale and small-scale mining operations in the area.

Geologically, the area represents the south westernmost extension of the well-studied Ashanti Gold Belt that accounts for over 90% of gold production in Ghana. There are six large gold projects and one manganese project in the area, along with about 30

Fig. 1 Location of study area



registered and over 20,000 unregistered small-scale mining operations. Metamorphosed sedimentary and volcanic rocks of the Birimian system and much smaller scattered shallow water sediments of Tarkwa system underlie the area.

The Prestea and Bogoso mines are located in what is locally called the Prestea Belt, stretching for more than 50 kms in north east-southwest direction. The rocks here consist of steeply dipping Birimian sediments and lavas that have been folded, overtrusted and intruded by felsic and basic sills and dykes. The specific rock units include: phyllite, greywacke, sericite-schist and tholeitic meta volcanics, dominated by carbonate alterations with pervasive quartz veining (Adadey 1983; Hirdes et al. 1992). Structural control of the mineralization, which occurs along several northeast trending structural features, from a few meters to several kilometres wide, has long been recognized (Junner 1935; Cooper 1934).

The Nsuta manganese mine, the only manganese mine in the country, is confined to the same stratigraphic horizon of metamorphosed volcano-sedimentary rocks as the Prestea and Bogoso mines. However, the manganese ore is hosted in carbonaceous meta sedimentary sequences. The ore consist of manganese oxides, manganese carbonates and transitional oxidation products locally called carbox (Nyame et al. 2002) and are sandwiched within phyllite horizons. The Damang, Tarkwa and Iduapriem mine sites, on the hand, are confined to the Tarkwaian Paleo sedimentary quartz conglomerates with scattered intrusions of felsic and basic dykes and sills.

Materials and methods

A total of 28 representative rock samples were collected from exposed lithological units, particularly in mining faces and rock outcrops, and mine spoil samples were obtained from mine waste dumps, spent heap leach stacks and tailings dumps from the three mines and their environs to assess their acid generation potential.

The individual samples were crushed in a jaw crusher to less than 5 cm and then grind in a ball mill to less than 125 μm. Two sub-samples, each of 50 g, were taken from each sample for ABA and NAGpH tests.

For the ABA test, paste pH, sulphide–sulphur (%), maximum acid potential (MAP), neutralization potential (NP) and the net neutralization potential (NNP), all expressed in $CaCO_3$ equivalent tons/1,000 tons material were determined by ABA method adapted from Smith et al. (1974) and modified by Sobek et al. (1978). The NNP was determined as the difference between the MAP and NP. The ratio of NP to MAP, known as neutralization potential ratio

(NPR) was then calculated for each of the samples tested. The NP of a sample was determined by adding known amounts of 0.2 N hydrochloric acid to a known sample weight, and then back titrating the solution with standard $CaCO_3$. The MAP, on the other hand, was determined as a percentage of sulphide–sulphur [MAP = 31.5, sulphide–sulphur content (%)]. The sulphide–sulphur content (%) was based on hydrogen peroxide oxidation of sulphide minerals after an acid leach to remove carbonate minerals. Any sulphide values below the detection limit of 0.0001 were assigned default 0% S and carried through in the subsequent calculations used.

For the net acid generation pH test, 2.5 g of each sub sample (pulverized) was reacted with 100 ml of 15% hydrogen peroxide to oxidize any reactive metal sulphides and the NAGpH of the reaction solution determined by titration with pH 7. This gives a value for the net acidity produced by the acid generation and neutralization reactions occurring in the sample (NAG) as outlined in Lawrence et al. (1990) and Miller (2000).

Results and discussion

The results of both acid base accounting and NAGpH tests are presented in Table 1. The results show available sulphur content in rocks to range from below detection to 0.79%, while neutralisation potential of the samples range from 11.23 to 285 kg CaCO3/ton. The sulphur content in the rocks as shown by the results of the ABA analysis appear generally lower than average sulphur content of gold ore in the Ashanti Belt which averages about 2%. The difference is from the fact that the material for this exercise was selected from exposed mining faces with little ore material.

Acid base accounting tests

The assumption for computations of the variables used to predict acid generation from ABA tests is that all of the available acid generating and acid neutralizing material is available to react. The theoretical foundation is that samples that have excess acid neutralizing materials will have lower probability of generating acidity than those that are deficient in neutralizing minerals Canadian Mine Environment Neutral Drainage (MEND) 2001. Theoretically, a sample with an excess of NP will not generate ARD. However, various empirical field works suggest that this is not generally true because of uncertainties created by differential reaction kinetics, leaching rates and mineral distribution in the rocks. Consequently, various workers on ARD studies have defined various criteria for characterizing the results of ABA test (Price et al. 1997, Canadian Mine Environment Neutral Drainage (MEND) 2001). A commonly applied screening criteria assumes that rocks with NNP values above 0 and NPR values below 1 are possibly acid-generating unless the sulphide content is less than 0.3% (AP < 10 kg/1,000), or the NPR is greater than 2 (Price et al. 1997).

If this criterion is used then none of the 28 samples is acid generating as all the samples returned NP/MAP or NPR values above four (Table 1). However, Smith et al. (2000) indicated that it is more appropriate to use primary data such as acid neutralizing capacity (ANC), maximum potential acidity (MPA) and sulphur values when interpolating static tests work rather than ratios. Characterization limits defined by Price et al (1997) are based on studies of coal deposits, which generally have high sulphur content. For low sulphide metal ores, such as those found within the Ashanti Metallogenic Belt in Ghana, Ferguson and Errington (1998) have indicated that samples with NNP values less than 20 kg $CaCO_3$/ton are likely to generate acid; those with NNP values greater than 20 kg $CaCO_3$/ton would not generate acid. Based on this criterion of categorization, four samples with NNP values ranging from 10.22 to 18.81 kg CaCO3/ton are acid generating. These samples are from: a dump of manganese oxide fines from Nsuta, (GMCTS01); an old tailings dump at Bondaye near Prestea, (PGRTDB01; material from a slightly weathered basic dyke GFRS01 and fresh basic GFRS07 from the Tarkwa mine) and the old Teberebie pit now exploited as part of the Tarkwa mine respectively (Fig. 2)

According to the United States Forestry Services when using the NPR criteria, an NP/MAP ratio of at least 5:1 should be required before a material is categorized to be non-acid forming (USDAFS 1992). Applying this caution to the samples from the study site, six samples with NPR values ranging from 4.16 to 4.94 are categorized as being at least "possibly acid forming". They are the manganese oxide fines, GMCTS01, phyllite material in the hanging wall of manganese ore GMCRS01, both from Nsuta; material from an old tailings dump at Bondaye near Prestea, PGRTSB01; material from the hanging wall phyllite PGRS03C, metagreywacke, PGRS06 and mineralized quartz reef PGRS07, all from the Prestea mine (Fig. 3)

The interpretation of the results from NAG tests on the samples follow the criteria outlined by the British Columbia Acid Mine Drainage Task Force (1989) and a similar one by the Australian Mineral Industries Research Association as summarized in Greenhill

Table 1 Results of acid base accounting and NAGpH tests

Location	Sample id	Sample type	Paste pH	Sulphur (%)	MAP	NP	NNP	NPR = NP/ MAP	NAGpH
Tarkwa mine	GFLMTS	Tailings from old dump	7.8	0.0001	0.003	44.3	44.30	14,063.49	6.4
	GFRC01	Felsic dyke	8.2	0.0279	0.879	45.57	44.69	51.85	6.0
	GFRC02	Quartz vein cutting dyke	8.2	0.0029	0.091	53.16	53.07	581.94	6.0
	GFRS01	Weathered basic dyke	7.6	0.0457	1.440	20.25	**18.81**	14.07	6.0
	GFRS02	Fine grained quartzite	8.0	0.0001	0.003	29.11	29.11	9,241.27	5.6
	GFRS03	Fine grained conglomerate	7.8	0.0464	1.462	32.91	31.45	22.52	6.2
	GFRS05	Fine grained quartzite	8.0	0.0556	1.751	63.29	61.54	36.14	6.6
	GFRS07	Fresh basic dyke	7.8	0.0371	1.169	11.39	**10.22**	9.75	6.7
Nsuta mine	**GMCTS01**	Reworked manganese oxide tailings	4.8	0.1584	4.990	21.85	**16.86**	**4.38**	**4.6**
	GMRS01	Phyllite above ore zone, hill D south crest	**6.3**	**0.3979**	**12.534**	61.91	49.376	**4.94**	**4.8**
	GMRS02C	Greenstone from hill D south crest	8.0	0.0554	1.745	170.89	169.14	97.93	7.0
	GMRS03C	Transition ore, hill D south crest	8.0	0.0369	1.162	126.58	125.42	108.90	7.1
	GMRS04	Carbonate ore from hill south crest	8.1	0.0288	0.90	110.13	109.22	121.40	6.1
	GMRS04C	Reworked manganese oxide tailings	7.5	0.0461	1.452	139.24	137.79	95.89	7.0
	GMRS05	Greenstone hill D north crest	7.3	0.0297	0.936	21.99	21.05	20.30	6.1
	GMRS06	Transition ore	8.3	0.0371	1.169	120.25	119.08	102.90	6.1
	GMRS07	Carbonate ore from hill D north crest	8.3	0.0297	0.936	31.65	30.71	33.83	6.5
	GMRS09	Phyllite below ore zone	7.2	0.5743	18.092	207.59	189.50	11.47	**5.0**
Prestea mine	PGRS01	Quartz vein	8.1	0.1386	4.366	221.52	217.15	50.74	6.6
	PGRS02	Dolerite dyke	8.0	0.0279	0.879	30.38	29.50	34.57	6.8
	PGRS03C	Phyllite (foot wall)	6.8	0.7861	24.762	103.13	78.37	**4.16**	**4.7**
	PGRS04	Ankerite alteration	8.2	0.0371	1.169	284.81	283.64	243.71	7.2
	PGRS06	Meta greywacke	6.8	0.4954	15.605	71.27	55.66	**4.57**	6.4
	PGRS07	**Mineralized quartz reef**	6.5	0.4346	13.690	67.09	53.40	**4.90**	**4.8**
	PGRS09	Unmineralized quartz reef	8	0.0371	1.169	39.24	38.07	33.58	5.8
	PGRS10	Siderite alteration	8	0.1201	3.783	292.41	288.63	77.29	8.6
	PGRTSB01	Tailings dump from Bondaye	3.7	0.2961	3.027	**13.92**	**10.89**	**4.60**	**4.5**
	PGRTSM	Old tailings from Tuapim	6.9	0.1016	3.200	60.76	57.56	18.99	6.1

Bold values are acid potential acid producing samples

(2000). According to these schemes, samples with NAGpH values less than three are considered strongly acid producing, those with values between three and five are acid generating and there may be some buffering taking place and samples with NAGpH values greater than five or six are considered not significantly acid producing or an alkaline sources is neutralizing the acid. Applying these criteria to the samples under investigation, six samples, with NAGpH values from 4.5 to 5.0, are considered acid generating and possibly

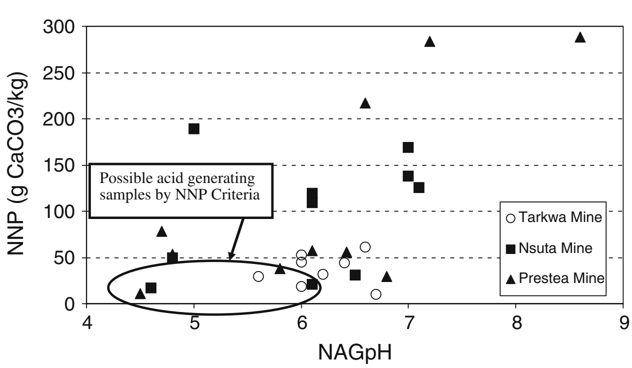


Fig. 2 NNP against NAGpH

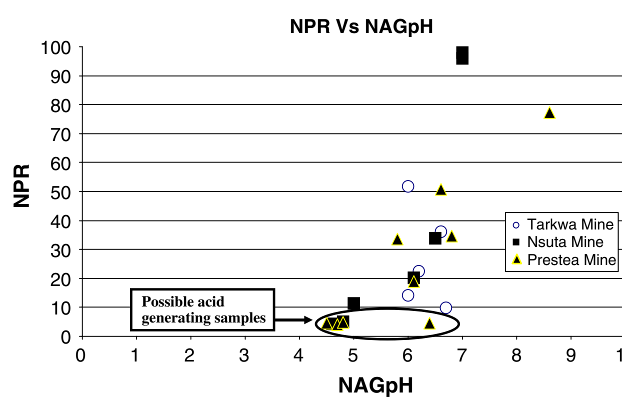


Fig. 3 NPR against NAGpH

have some alkaline buffering taking place. These are the manganese oxide fines from Nsuta, GMCTS01; hanging and footwall phyllite of the ore zone in hill D south crest, GMCRS01 and GMRS09 respectively, from Nsuta; mineralized quartz reef, PGRS07, the hanging wall phyllite PGRS03C and material from old tailings dump from Bondaye, PGRTSB01, all from the Prestea mine.

Consistency of tests results

The results of NAGpH tests and the ABA have been nearly consistent. Both methods commonly identified five samples as being potentially acid generating out of the six and eight samples respectively identified by the individual methods as being acid generating (Table 2). Two of the samples GFRS01 and GFRS07, presenting sample from basic dykes from the Tarkwa mine site which have been classified as possible acid generating based on their NP values, have been classified as non-acid generating from NAGpH tests results. These two samples have extremely low sulphur values and correspondingly low NP values. The extremely low sulphur values in these samples practically preclude the possibility of acid production when such rocks are weathered.

Managing problematic wastes

There is a growing realization that the cost of treating mining wastes that have the potential to generate acid drainage or 'problematic waste' can be very high, but if the sources can be identified, then their selective treatment may be more cost effective than the treatment of much larger quantities of non-problematic material with which problematic material is arbitrarily classified (Downing et al. 2000). This exploratory study has been successful in identifying the various problematic lithological units likely to be encountered during mining in all the three mines investigated. At the Prestea mine site, the phyllite and greywacke units, the mineralized quartz reefs and the old tailings dump at Bondaye exhibit potential for acid generation. At the Nsuta mine site, the phyllite Zones (hanging and foot wall phyllite), encapsulating the carbonate ore and old manganese oxide tailings been reworked are also potentially acid generating.

The results of the study also show that at all the mine sites there are also lithological units with excessive carbonate or acid neutralizing capacity, with significant net neutralization potential ranging from 50 to 280 kg $CaCO_3$/ton (Table 1). This combination of possible acid generating strata and possible acid neutralizing strata could effectively be harnessed to prevent acid generation in the various mine sites. Calculated blending of possible acid generating and acid neutralizing waste rock at the waste dumpsite could ensure in situ neutralization of acid drainage and immediate immobilization of any heavy metals associated with such drainage. This would, however, require further investigation of these samples using kinetic methods to determine their leaching rates.

The results show that NAGpH test is a sufficient, but simple cost effective and rapid kinetic test that can effectively confirm ARD test results, particularly in low sulphide and low carbonate environment. While it might be too early to recommend the possible use of NAGpH test in lieu of ABA, it is an effective complementary test to confirm acid generating potential of mine waste.

Conclusions

Based on all the criteria used, the two tailings dumps, GMCTS01 and PGRTSB01, at Nsuta and other samples, representing phyllite encapsulating manganese ore at Nsuta, phyllite, Bondaye, near Prestea, respectively, have consistently passed the test as acid generating, while five meta greywacke and quartz veins within periphery of ore zone in Prestea and two basic dykes from the defunct Teberibie mine, near Tarkwa, respectively passed as possible acid producing by one criteria alone would need further investigation to reach firm conclusions.

As a screening exercise, one would consider all seven samples as potentially acid generating, unless later works prove them otherwise, and that mines encountering these lithologies should take the necessary precautions of isolating them in their mine waste management programmes

Table 2 Acid generating material by a variety of criteria

Acid base accounting tests			NAGpH
NP < 1	NNP < 20 kg $CaCO_3$/ton	NPR of 5:1	NAGpH less than 5
None	GMCTS01, GRTDB01, GFRS01 and GFRS07	GMCTS01, GMCRS01 PGRTSB01, PGRS03C, PGRS06 and PGRS07	GMCTS01, GMCRS01, GMCRS09, PGRS03C, PGRS07 and PGRTSB01

The results shows that acid base accounting and net acid generating pH tests are sufficient and complementary tools to screen mine spoil for their acid generating status in low sulphide mineralization environments such as the Ashanti Metallogenic Belt of Ghana. Their use as routine tools for assessment of ARD, particularly in environmental impact assessment of mining projects, should be encouraged because of their relatively low cost.

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