PRELIMINARY EVALUATION OF ACID MINE DRAINAGE IN MINAS GERAIS STATE, BRAZIL[1]

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SUMMARY

Mining in the State of Minas Gerais-Brazil is one of the activities with the strongest impact on the environment, in spite of its economical importance. Amongst mining activities, acid drainage poses a serious environmental problem due to its widespread practice in gold-extracting areas. It originates from metal-sulfide oxidation, which causes water acidification, increasing the risk of toxic element mobilization and water resource pollution. This research aimed to evaluate the acid drainage problem in Minas Gerais State. The study began with a bibliographic survey at FEAM (Environment Foundation of Minas Gerais State) to identify mining sites where sulfides occur. Substrate samples were collected from these sites to determine AP (acidity potential) and NP (neutralization potential). The AP was evaluated by the procedure of the total sulfide content and by oxygen peroxide oxidation, followed by acidity titration. The NP was evaluated by the calcium carbonate equivalent. Petrographic thin sections were also mounted and described with a special view to sulfides and carbonates. Based on the chemical analysis, the acid-base accounting (ABA) was determined by the difference of AP and NP, and the acid drainage potential obtained by the ABA value and the total volume of material at each site. Results allowed the identification of substrates with potential to generate acid drainage in Minas Gerais state. Altogether these activities represent a potential to produce between 3.1 to 10.4 billions of m^3 of water at pH 2 or 31.4 to 103.7 billions of m^3 of water at pH 3. This, in turn, would imply in costs of US$ 7.8 to 25.9 millions to neutralize the acidity with commercial limestone. These figures are probably underestimated because some mines were not surveyed, whereas, in other cases, surface samples may not represent reality. A more reliable state-wide evaluation of the acid drainage potential would require

further studies, including a larger number of samples. Such investigations should consider other mining operations beyond the scope of this study as well as the kinetics of the acid generation by simulated weathering procedures.

Index terms: acid mine drainage, acid-base accounting; sulfide minerals.

RESUMO: *AVALIAÇÃO PRELIMINAR DE DRENAGEM ÁCIDA NO ESTADO DE MINAS GERAIS, BRASIL*

A despeito da importância econômica de atividades mineralógicas para o estado de Minas Gerais, perceber-se que elas causam significativo impacto ao ambiente. Drenagem ácida é um dos aspectos ambientais considerados pela atividade em função de seus impactos. Ela tem origem a partir da oxidação de sulfetos metálicos que acidificam as águas, com possibilidade de mobilizar elementos tóxicos e poluir os recursos hídricos. Este trabalho teve como objetivo realizar uma avaliação preliminar do problema em Minas Gerais. O trabalho teve início a partir de um levantamento bibliográfico junto a Fundação Estadual de Meio Ambiente (FEAM) para identificar minerações cujo minério está associado a sulfetos. Amostras dos substratos foram retiradas para determinar o potencial de acidez (AP) e de neutralização (NP). AP foi avaliado por dois procedimentos: pelo teor total de sulfetos e pela oxidação com peróxido seguida da titulação ácida. O NP foi avaliado pelo teor equivalente de carbonato de cálcio. Lâminas petrográficas foram preparadas para a descrição mineralógica com ênfase em sulfetos e carbonatos. O balanço ácido-base (ABA) foi determinado pela diferença entre AP e NP, enquanto o potencial de geração de águas ácidas foi obtido pelo valor de ABA e o volume total de material de cada atividade minerária. Os resultados permitiram identificar quatro substratos com potencial para gerar drenagem ácida no estado de Minas Gerais. Juntas, estes materiais representam um potencial de geração de cerca 3,14 a 10,37 bilhões de metros cúbicos de água a pH 2,0 ou 31,4 a 103,7 bilhões de metros cúbicos de água a pH 3,0. Estes valores significam custos entre US$ 7,8 e 25,9 milhões para neutralizar a acidez com o uso de calcário. Estas estimativas são provavelmente subavaliadas, uma vez que algumas minerações não foram incluídas no levantamento e, para outras, as amostras superficiais podem não representar a realidade. Uma avaliação mais rígida do potencial de drenagem ácida em nível estadual requer estudos futuros. Estes estudos precisariam incluir um número maior de amostras e mineradoras não incluídas neste trabalho. Eles poderiam considerar, ainda, a cinética de geração de acidez por meio de procedimentos de intemperismo simulado.

Termos de indexação: drenagem ácida de minas; balanço ácido-base; minerais sulfetados.

INTRODUCTION

Mining is one the most important traditional and economical activities in Brazil, which accounts for considerable economic and social benefits. Nevertheless, mining is considered to cause a number of negative environmental impacts. Acid mine drainage (AMD) is one of the currently most discussed environmental problems. It is initiated during the mining process, where a variety of metallic sulfides is exposed to the atmosphere and spontaneously oxidizes in the presence of O_2 (Geidel & Caruccio, 2000). Sulfide materials may also be exposed by highway construction and other large scale excavations (Skousen, 2000). The products of such reactions are not only highly soluble, but also strongly acidic. Thus, high sulphate and iron contents make the water drainage acid. If potentially toxic elements are present, such as Al, Mn, Cu, Zn, Pb, Hg, Cd, etc., they are mobilized in the drainage water, increasing the risk of toxic metal incorporation in biological systems, promoting biomagnification by the trophic chain (Mello & Abrahão, 1998). Among the sulfide minerals, pyrite and marcasite (FeS_2) are dominant in the state's mining regions, but other metals may be complexed with these sulfides, forming chalcopyrite ($CuFeS_2$), covellite (CuS), galena (PbS), sphalerite (ZnS), and arsenopyrite ($FeAsS$).

In Brazil, AMD studies are recent, and the problem has been reported in coal mines in the states of Rio Grande do Sul and Santa Catarina (Soares, 1995). There are many mines in the state of Minas Gerais where sulfides are associated with manganese, gold, nickel, zinc, lead and uranium, with the potential to generate acid mine drainage (Santana Filho, 2000).

The pH values of acid drainage (AD) in mined areas is usually below 3.5, with total amounts of soluble metals of over 50 mg L^{-1} (Ziemkiewics et al., 1977). In fact, high metal concentrations are common in acid drainage from coal mines, where average values of Fe and Mn in solution can vary from 20 to 300 mg L^{-1} and sulfate from 20 to 2,000 mg L^{-1} (Richards et al., 1993).

An important aspect to control the occurrence of AD is an accurate prediction of the acid-producing potential of the material. Several methods of determining the acidity potential (AP) have been proposed, for example: Smittenberg et al. (1951); Neckers & Walker (1952); Murthy & Sharada (1960); Pons (1964); Petersen (1969); Aspiras et al. (1972); Caruccio (1975); and Sorenson et al. (1979). In Brazil, Soares et al. (1997) used the "aqua regia" (HNO_3:HCl 1:3) digestion as a simplified method to evaluate the total sulfide content in coal mining samples from Rio Grande do Sul. Each of these methods measures either S or Fe associated with iron sulfides and therefore provides an indirect estimate of the potential acidity by the stoichiometric equation for pyrite oxidation. The constraints on such estimates are that sulfides other than pyrite may be present, which produce acidity in a different stoichiometry in relation to that of pyrite, as described by Singer and Stumm (1970). Such estimates would therefore require a detailed description and an accurate evaluation considering all sulfides present in the sample, which is a very laborious and demanding determination. To overcome this problem, the acid-producing potential can be measured directly. A rapid oxidation technique has been proposed with 30 % H_2O_2 that oxidizes iron sulfides (Yoneda, 1961; Grube Jr. et al., 1971; Sobek et al., 1978), followed by a direct titration of the produced acid.

The occurrence of AMD is not only determined by the presence of sulfides since it is very common to find carbonates associated with sulfides, which may reduce or neutralize the acidity generated by sulfide oxidation. Acid-Base Accounting (ABA) is a widely used method to estimate the potential of acid generation (Sobek et al., 1978). It is calculated by the difference between the acidity (AP) and neutralization potential (NP). In the case of negative values, the neutralization potential of the substratum is higher than its potential of acidity and AMD is, therefore, not expected.

With regard to the fact that Brazilian environmental regulations are yet incipient concerning AMD aspects, the scope of the problem needs to be evaluated. It is therefore important to identify suitable simple analytical methods for such an assessment. The "aqua regia" digestion appears to be a simple enough option for AMD studies.

The present study aimed to compare direct measures of the acid-producing potential technique as described by O'Shay et al. (1990) with the total sulfide oxidation evaluated by the "aqua regia" digestion technique. Furthermore, the potential of some mining activities in the state of Minas Gerais, Brazil to generate acid drainage was outlined in a preliminary evaluation.

MATERIAL AND METHODS

In a thorough bibliographic survey at the Minas Gerais Environmental Agency (FEAM), sites where mining activities are associated with sulfides were identified. Seven large mining sites were listed whose activities have the potential to generate acid drainage, including uranium, nickel, gold, and zinc exploitations. The second step consisted in the sampling of the different substrates including ore, overburden, and tail (Table 1) according to the peculiarities of each mine. In all situations, at least three simple surface (0–0.2 m) samples were taken to compose the final sample.

After each sample had been dried and ground (0.149 mm), analyses were carried out to determine the pH and electrolytic conductivity (EC) in water (1:2.5 v/v), the acidity potential (AP) and neutralization potential (NP). AP was evaluated by two procedures: total sulfide content after HCl + HNO_3 mixture (3:1 v/v) digestion (Soares, 1995) and oxygen peroxide (30 %) oxidation followed by acidity titration (O'Shay et al., 1990). NP was evaluated as calcium carbonate equivalent by titration of the remaining HCl after reaction with a ground sample (Embrapa, 1979). Based on the chemical analysis, the acid-base accounting (ABA) was determined by the difference of AP and NP. The generation potential of acid drainage was obtained from ABA values and the total amounts of the respective materials of each mining activity. This potential was stated as acid water volume at pH 2.0 or 3.0.

Petrographic thin sections were produced after impregnating representative rock samples from each site. The main minerals were described, focusing on the presence of sulfite/carbonate. Sulfites were identified based on the following criteria (Winchell, 1933; Kerr, 1977):

- Pyrite (FeS_2) was identified by cubic to octahedral crystals, opaque, showing a brilliant metallic luster, creamy white color under reflected light and yellowish colors under dimmed reflected light.

- Sphalerite (ZnS) was identified by isotropic tetrahedral crystals, with refringence, brownish to yellow color, with spectral tonality.

- Pyrrhotite (FeS) was identified by hexagonal prism, opaque crystals, produced marked rotation of the polarization plane under

Table 1. Description of different materials sampled at each mining site

Site	Ore	Sampled material	Point of sampling
A	Uranium	Overburden	Surface samples at the bottom, center and top of the piles.
B	Nickel	High content, intermediate and low content ores, overburden and tailing.	Ore and overburden sampled from piles and tailing from tailing ponds.
C	Gold	Two kinds of non-oxidized ore B1 and B2	Ore sampled directly from the mining area.
D	Gold	Ore, tailing and overburden	Ore sampled from piles and tailing from tailing ponds
E	Gold	Ore, overburden and tailing	Ore and overburden sampled from the piles and tailing from tailing ponds.
F	Zinc	Ore and tailing	Ore and tailing sampled from piles.
G	Zinc and lead	Ore, overburden and tailing	Overburden from piles, ore from the strap loader and tailing from tailing ponds

reflected light; Color yellow to copper, darker than pyrite; cream-colored under vertical reflected light; usually associated with chalcopyrite.

- Arsenopyrite (FeAsS) with octahedral to subhedral prismatic crystals, silvery white to grayish, white color under vertical reflected light, commonly intergrown with chalcopyrite and especially pyrite.

- Chalcopyrite (CuFeS) was identified by tetrahedral crystals, often striated, of brass-yellow color, light yellow under vertical reflected light; there was no visible plane rotation under polarized reflected light.

In the overall discussion the mining companies were identified by letters rather than by names, hence preserving their legal rights and to avoid ethical issues.

RESULTS AND DISCUSSION

pH, electrolytic conductivity, sulfur and carbonate contents

According to the pH values, the samples were classified in two groups. The first one had low to very low pH values (2.6 to 5.4) and included samples from sites A, B, and C (Table 2), with exception of site B overburdens which presented lower sulfide content and the presence of carbonates. The group formation was corroborated by the microscopic observation of thin sections under high magnification (Figure 1). The low pH suggests the presence of sulfides and, possibly, AMD. The second group, including samples from sites D, E, F, and G, showed high pH values (> 7.0) due to the substantial presence of carbonates. Among all sites, the highest (9.5) as well as lowest (5.5) pH values were observed in tails from a gold mining site.

The high pH values associated with the presence of carbonates are in agreement with the geology of each area. Samples from sites F and G showed high pH values due to the dominance of carbonates in the limestone and dolomites of the Bambuí Group. Samples from sites D and E showed high pH values ascribed to the presence of carbonates associated to the Banded Iron Formation (BIF) of the Rio das Velhas Supergroup. In such cases, not only calcium (calcite) and magnesium (dolomite), but also iron (siderite) are expected. It is worth mentioning that the presence of siderite in a sample can overrate its neutralization potential (Caruccio and Geidel, 1996). Higher pH values than expected in a saturated $CaCO_3$ solution in equilibrium with atmospheric CO_2 are probably associated with the presence of salts or hydroxides, arising from the mineral concentration process.

The EC results showed greater variability than pH. Values ranged from 0.04 dS m^{-1} in ore B1 from site C to 17.56 dS m^{-1} in tailing from site D. The highest EC values are expected in tailing samples due to the mineral concentration process. In general, EC values are higher in samples containing sulfides and are associated with the AMD process. Sulfide oxidation involves solubilization reactions that increase the ionic activity and, consequently, raise EC values.

Acid base accounting

The different ABA values resulting after subtracting the acidity (AP) from the neutralization potential (NP) (Table 3) only allowed an identification of the AMD potentiality in overburden samples from

Table 2. pH and electrolytical conductivity values and total sulfur and carbonate content of the materials sampled at each mining company

Company	Sample	pH	CE	S	CaCO₃
			dS m⁻¹	——————— g kg⁻¹ ———————	
A	Overburden 1a	4.43	1.46	23.4 ± 0.076	0
	Overburden 1b	3.93	1.51	14.1 ± 0.003	3.9 ± 0.285
	Overburden 1c	2.69	2.78	8.5 ± 0.022	4.8 ± 0.139
	Overburden 1d	3.76	1.75	9.6 ± 0.057	9.9 ± 0.277
	Overburden 2	3.87	2.10	19.4 ± 0.035	2.6 ± 0.655
	Overburden 3a	3.35	1.78	14.9 ± 0.055	0.4 ± 0,674
	Overburden 3b	4.03	1.24	8.9 ± 0.025	8.3 ± 0.612
	Overburden 3c	4.37	2.06	7.7 ± 0.031	1.4 ± 0.279
	Overburden 3d	4.06	1.75	7.6 ± 0.022	0
	Overburden 3e	3.82	1.66	9.8 ± 0.006	1.5 ± 0.618
	Overburden 4	2.63	4.22	41.7 ± 0.209	0
B	Ore 1 (High)	3.45	7.56	189.0 ± 1.327	6.4 ± 0.550
	Ore 2 (Medium)	4.26	4.21	113.6 ± 0.869	14.5 ± 0.004
	Ore 3 (Low)	4.57	3.04	23.4 ± 0.080	33.2 ± 0.837
	Overburden 1	6.45	1.25	0.8 ± 0.006	55.3 ± 0.277
	Overburden 2	8.22	0.30	10.7 ± 0.022	44.1 ± 2.798
	Tail	3.05	9.28	26.1 ± 0.059	45.0 ± 0.293
C	Ore B2a	4.07	1.11	6.7 ± 0.024	3.8 ± 0.650
	Ore B2b	4.19	0.45	9.6 ± 0.020	23.1 ± 0.288
	Ore B2c	4.59	0.30	3.2 ± 0.028	0
	Ore B2d	4.21	1.66	8.7 ± 0.067	19.8 ± 0.276
	Ore B1a	5.38	0.04	1.1 ± 0.008	3.9 ± 0.138
	Ore B1b	4.85	0.07	1.0 ± 0.010	4.4 ± 0.609
D	Overburden 1	7.94	0.11	1.1 ± 0.011	55.8 ± 0.262
	Ore 1	7.98	1.39	47.7 ± 0.464	173.7 ± 2.901
	Ore 2	8.33	0.28	49.0 ± 0.063	180.5 ± 9.657
	Tail 1	8.04	2.00	3.3 ± 0.016	220.4 ± 13.026
	Ore 3	6.73	0.12	1.3 ± 0.004	51.8 ± 0.549
	Overburden 2	8.11	0.13	0.8 ± 0.004	55.2 ± 0.287
	Overburden 3	6.63	0.03	2.6 ± 0.004	43.1 ± 0.569
	Overburden 4	8.48	0.22	2.2 ± 0.011	243.6 ± 1.218
	Tail 2	7.87	0.93	11.9 ± 0.046	201.0 ± 0.583
	Tail 3	8.05	0.87	3.8 ± 0.024	232.7 ± 0.558
	Tail 4	9.51	2.33	9.1 ± 0.021	39.7 ± 0.278
	Tail 5	5.51	17.56	116.5 ± 0.079	256.8 ± 0.539
E	Overburden	8.49	0.39	6.4 ± 0.063	75.0 ± 0.285
	Ore	8.00	0.56	33.5 ± 0.161	142.7 ± 0.970
	Tail	8.02	2.31	21.7 ± 0.069	113.0 ± 0.305
F	Ore	8.88	0.16	1.9 ± 0.010	203.2 ± 1.240
	Tail	8.65	0.07	2.4 ± 0.015	763.2 ± 14.272
G	Ore	8.89	0.31	34.6 ± 0.217	916.4 ± 1.100
	Tail	7.70	2.04	18.1 ± 0.172	978.2 ± 2.543
	Overburden	9.24	0.24	18.2 ± 0.058	991.0 ± 2.676

Figure 1. Photomicrograph under transmitted light with crossed polarizers showing crystals of pyroxene (px), amphibole (af), epidote (ep) and carbonate (cb).

site A, ore samples from site C, ore and tail samples from site B, and in an old tail (5) from site D. The ABA estimates resulted in different values of acid drainage potential according to the adopted criteria. Table 3 shows that the total sulfide content criteria resulted in higher ABA values, probably due to the presence of other sulfides such as chalcopyrite (samples from sites B and C), sphalerite (site A) and pentlandite (site B), as well as arsenopyrite (sites A, C, and E) besides pyrrhotites. The presence of such a variety of sulfide minerals, identified by petrographic observation (Figures 2 to 6), may have resulted in overestimated ABA values since the acid generation reactions from these sulfides probably have an stoichiometry other than pyrite. In this

Table 3. Acidity potential (AP) obtained by total S and H_2O_2 procedures, neutralization potential (NP) and acid-base accounting (ABA) values for different materials sampled at each mining company

Company	Sample	AP		NP	ABA	
		Total S	H_2O_2		Total S	H_2O_2
				———— mol t^{-1} ————		
A	Overburden 1[a]	1463	923	0	1463	923
	Overburden 1b	881	478	77	804	401
	Overburden 1c	531	103	97	434	6
	Overburden 1d	600	256	199	401	57
	Overburden 2	1213	291	51	1162	240
	Overburden 3a	931	1316	9	922	1307
	Overburden 3b	556	222	167	389	55
	Overburden 3c	481	120	28	453	92
	Overburden 3d	475	85	0	475	85
	Overburden 3e	613	256	30	583	226
	Overburden 4	2606	683	0	2606	683
B	Ore (high)	11813	8202	128	11685	8074
	Ore (Intermediate)	7100	5020	289	6811	4731
	Ore (low)	1463	513	665	798	-152
	Overburden 1	50	0	1106	-1056	-1106
	Overburden 2	669	555	881	-212	-326
	Tail	1631	1487	900	731	587
C	Ore B2a	419	256	75	344	181
	Ore B2b	600	410	462	138	-52
	Ore B2c	197	129	0	197	128
	Ore B2d	544	307	397	147	-90
	Ore B1a	69	0	79	-10	-79
	Ore B1b	63	0	88	-25	-88
D	Overburden 1	69	325	1116	- 1047	- 791
	Ore 1	2981	814	3475	- 494	- 2661
	Ore 2	3063	673	3610	- 547	- 2937
	Tail 1	206	359	4408	- 4202	- 4049
	Ore 3	81	34	1036	- 955	- 1002
	Overburden 2	50	17	1103	- 1053	- 1086
	Overburden 3	163	51	862	- 699	- 811
	Overburden 4	138	0	4872	- 4734	- 4872
	Tail 2	744	0	4019	- 3275	- 4019
	Tail 3	238	547	4655	- 4417	- 4108
	Tail 4	569	68	794	- 225	- 726
	Tail 5	7281	7156	5136	2145	2020
E	Overburden	400	0	1499	- 1099	- 1499
	Ore	2094	854	2855	-761	-2001
	Tail	1356	239	2261	-905	-2022
F	Ore	119	0	4064	-3945	-4064
	Tail	150	137	15264	-15114	-15127
G	Ore	2163	0	18328	-16165	-18328
	Tail	1131	0	19564	-18433	-19564
	Overburden	1138	0	19820	-18682	-19820

case, AP estimates of the total S content, after "aqua regia" digestion, were calculated on the basis of pyrite oxidation stoichiometry, as described by Singer & Stumm (1970). On the other hand, estimates from H_2O_2 oxidation by the method of O´Shay et al. (1990) are probably underestimated, due to incomplete sulfide oxidation, as verified by Corrêa et al. (2002). An evaluation of the true potential of generating acid water, the costs and environmental risks must consider the peculiarities of each situation. The actual values probably range somewhere between the estimates of both criteria.

AMD estimates

The ABA values, in mols per metric ton (Table 3) were converted to liters per metric ton of acid water at pH 2.0 or 3.0. The total acid water volumes were calculated from the ABA values versus the mass (in metric tons) of each material (Tables 4 and 5). The calculations were only carried out for samples with an acid drainage potential (i.e., with positive ABA values), taking the mean values of the same materials. Thus, the estimates of acid drainage reached 13.3×10^9 m^3 of acid water at pH 2.0, or

Figure 2. Photomicrograph under reflected light with parallel polarizers showing intergrowing of chalcopyrite (cp) droplets in pyrrhotite (po) as anhedral crystals, and magnetite (mg) as anhedral mass.
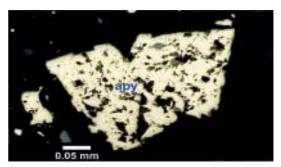

Figura 5. Photomicrograph under transmitted light with parallel polarizers. In the picture subhedral to euhedral arsenopyrite (apy) crystals.
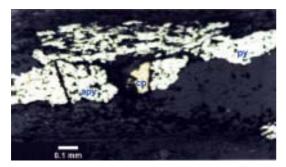

Figure 3. Photomicrograph under reflected light with parallel polarizers. In the picture intergrowing of chalcopyrite (cp), pyrite (py) and arsenopyrite (apy).

Figure 6. Photomicrograph under reflected light with parallel polarizers. In the picture euhedral arsenopyrite (apy) crystal wrapped in anhedral mass of pyrrhotite (po).
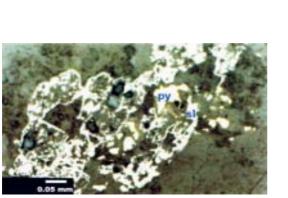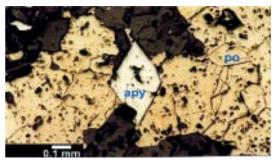

Figure 4. Photomicrograph under reflected light with parallel polarizers showing anhedral crystals of pyrite (py) and ground mass of sphalerite (sl) at the center.

132.8 x 10^9 m^3 at pH 3.0 according to the calculations, and considering the total S content extracted by "aqua regia" (Table 4). On the other hand, the hydrogen peroxide criteria presented estimates of around 5.9 x 10^9 m^3 with pH 2.0 or 58.9 x 10^9 m^3 with pH 3.0 (Table 5). The real contribution to the acid drainage generation depends on the different mitigation measures adopted by local companies, as mentioned below.

In the case of site A, mining activities have ceased and acid water arises from the sampled overburdens. Thus, the estimate of acid drainage for site A is between 2.42 and 5.28 x 10^9 m^3 of acid water at pH 2.0 or 24.2 to 52.8 x 10^9 m^3 at pH 3.0 (Tables 4 and 5). It is known that the company mitigates the problem by damming and neutralizing the acid water. Besides, the overburden piles were covered with clayey soil to seal them.

Site B has a potential for acid drainage generation of around 2.24 x 10^9 m^3 of acid water at pH 2.0 or 22.4 x 10^9 m^3 at pH 3.0, according to the lowest estimate criterion (Table 5). Nevertheless, ore processing at this mine includes a plant for sulphuric acid production, which decreases acid generation by 68.1 %, from 421,767 L t^{-1} in the ore to 58,700 L t^{-1} in tailing, according to the lowest estimate at pH 2.0. Calculations of the acid water generation should therefore take into consideration that 46 % of the ore is converted into tailing (Brandt, 1996). Thus, 5,207,066 t of ore produce around 2,395,250 t of tailing and the acid generation potential would be between 185 and 230 millions m^3 of water at pH 2.0 or 1.85 to 2.30 x 10^9 m^3 at pH 3.0 (Table 6). Another consideration is that approximately a third part of

Table 4. Acid water generation potential with pH 2.0 and pH 3.0, as estimated by the total sulfide content criteria for different materials sampled at each mining company

Company	Sample	Acid water volume (L t⁻¹)		Mass of materials (t)	Acid water volume (1.000 L)	
		pH 2	pH 3		pH 2	pH3
A	Overburden 1a	146,300	1,463,000			
	Overburden 1b	80,400	804,000			
	Overburden 1c	43,400	434,000			
	Overburden 1d	40,100	401,000			
	Mean Overburden 1	77,550	775,500	34,650,000	2.69×10^9	2.69×10^{10}
	Overburden 2	116,200	1,162,000	5,520,000	6.41×10^8	6.41×10^9
	Overburden 3a	92,200	922,000			
	Overburden 3b	38,900	389,000			
	Overburden 3c	45,300	453,000			
	Overburden 3d	47,500	475,000			
	Overburden 3e	58,300	583,000			
	Mean Overburden 3	56,440	564,400	28,520,000	1.61×10^9	1.61×10^{10}
	Overburden 4	260,600	2,606,000	1,293,600	3.37×10^8	3.37×10^9
	Total				5.28×10^9	5.28×10^{10}
B	Ore (high)	1,168,500	11,685,000			
	Ore (Intermediate)	681,100	6,811,000			
	Ore (low)	79,800	798,000			
	Mean of the ores	643,133	6,431,330	5,207,066	3.35×10^9	3.35×10^{10}
	Tail	73,100	731,000	750,000	5.48×10^7	5.48×10^8
	Ore B2a	34,400	344,000			
	Ore B2b	13,800	138,000			
C	Ore B2c	19,700	197,000			
	Ore B2d	14,700	147,000			
	Mean Ore B2	20,650	206,500	203,231,491	4.20×10^9	4.20×10^{10}
D	Tail 5	214,500	2,145,000	1,859,850	3.99×10^8	3.99×10^9
Total					13.28×10^9	13.28×10^{10}

Table 5. Acid water generation potential with pH 2.0 and pH 3.0, as estimated by the H_2O_2 digestion criteria for different materials sampled at each mining company

Company	Sample	Acid water volume (L t⁻¹)		Mass of material (t)	Acid water volume (1.000 L)	
		pH 2	pH 3		pH 2	pH3
A	Overburden 1a	92,300	923,000			
	Overburden 1b	40,100	401,000			
	Overburden 1c	600	6,000			
	Overburden 1d	5,700	57,000			
	Mean Overburden 1	34,675	346,750	34,650,000	1.20×10^9	1.20×10^{10}
	Overburden 2	24,000	240,000	5,250,000	1.26×10^8	1.26×10^9
	Overburden 3a	130,700	1,307,000			
	Overburden 3b	5,500	55,000			
	Overburden 3c	9,200	92,000			
	Overburden 3d	8,500	85,000			
	Overburden 3e	22,600	226,000			
	Mean Overburden 3	35,300	353,000	28,520,000	1.01×10^9	1.01×10^{10}
	Overburden 4	68,300	683,000	1,293,000	8.83×10^7	8.83×10^8
	Total				2.42×10^9	2.42×10^{10}
B	Ore (high)	807,400	8,074,000			
	Ore (Intermediate)	473,100	4,731,000			
	Ore (low)	-15,200	-152,000			
	Mean of all ores	421,767	4,217,670	5,207,066	2.20×10^9	2.20×10^{10}
	Tail	58,700	587,000	750,000	4.40×10^7	4.40×10^8
C	Ore B2a	18,100	181,000			
	Ore B2b	-5,200	-52,000			
	Ore B2c	12,800	128,000			
	Ore B2d	-9,000	-90,000			
	Mean Ore B2	4,175	41,750	203,231,491	8.48×10^8	8.48×10^9
D	Tail 5	202,000	2,020,000	1,859,850	3.76×10^8	3.76×10^9
Total					5.89×10^9	5.89×10^{10}

the tails is destined for landfills of the underground mine, jointly with the overburdens. In this situation it is possible that, depending on the physical conditions and mixture quality, the overburden with a negative ABA will further neutralize the acidity tailing causes. Such considerations would suggest a more optimistic estimate of the acid drainage potential at site B (Table 6).

At site C, only ores were sampled, since there were no overburden piles. In this case, the AMD potential depends on the quantities and composition of the ores to be processed, as well as on the sulfide recovery rate during the process. The proportion of each ore type in the blend depends on the gold price, which is rather variable. Nevertheless, a gold price of US$ 325.00 per oz can be assumed. In this case, the blend composition would be 72 % of ore B2 (227,054,880 t) and 24 % of ore B1 (88,299,120 t) to be exploited and processed from 1998 to 2014. Hence, the potential for acid drainage generation would be as shown in Table 7.

Considering a minimum recovery rate of 58 % for sulfides at the "flotation" process, the acid drainage potential at the tailing dam would be only 42 % of the estimate in Table 7. The difference corresponds to the material to be settled in pools, where environmental control measures are strict. The AMD estimate for site C was 211×10^6 to 4.53×10^9 m^3 of acid water at pH 2.0 or 2.11 to 45.3×10^9 m^3 at pH 3.0 (Table 7). These values are lower than the ones established by Pinto and Nepomuceno (1998). The reason for this difference is probably the surface sampling done at the "mining front". Under such conditions, the B2 samples could be partially oxidized and might not represent the sulfide body as deeper probe sampling would.

At site D, an old tail dam (tail 5) is a potential acid drainage generator (Table 3), estimated similarly by both criteria at 376 to 399×10^9 m^3 of acid water at pH 2.0 (Table 4 and 5). It is known that the dam is lined with clayey soil and environmental control is probably increasing. Nevertheless, the AMD

Table 6. Acid water generation potential of company B samples

Sample	Acid water volume (L t⁻¹)		Mass of material (t)	Acid water volume (1.000 L)	
	pH2	pH3		pH2	PH3
TSC criteria					
Actual tail	73,100	731,000	750,000	5.48×10^7	5.48×10^8
Future tail	73,100	731,000	2,395,250	1.75×10^8	1.75×10^9
Total			3,145,250	2.30×10^8	2.30×10^9
Dammed tail	73,100	731,000	2,201,675	1.61×10^8	1.61×10^9
H$_2$O$_2$ criteria					
Actual tail	58,700	587,000	750,000	4.40×10^7	4.40×10^8
Future tail	58,700	587,000	2,395,250	1.41×10^8	1.41×10^9
Total				1.85×10^8	1.85×10^9
Dammed tail	58,700	587,000	2,201,675	1.29×10^8	1.29×10^9

Table 7. Acid water generation potential of company C samples

Sample	Acid water volume (L t⁻¹)		Mass of materials (t)	Acid water volume (1.000 L)	
	pH2	pH3		pH2	PH3
TSC criteria					
B1	-1,750	-17,500	88,299,120	-1.55×10^8	-1.55×10^9
B2	20,650	206,500	227,054,880	4.69×10^9	4.69×10^{10}
Mean				4.53×10^9	4.53×10^{10}
H$_2$O$_2$ criteria					
B1	-8,350	-83,500	88,299,120	-7.37×10^8	-7.37×10^9
B2	4,175	41,750	227,054,880	9.48×10^8	9.48×10^9
Mean				2.11×10^8	2.11×10^9

Table 8. Acid drainage evaluation potential and costs for neutralization based on total sulfide content (TSC) of samples and the H_2O_2 digestion criteria

Company	Acid water volume (x 10^9 m^3)		Limestone amount (x 10^6 t)	Neutralization cost (US$)
	pH2	pH3		
TSC criteria				
A	5.28	52.80	2.64	13,200,000.00
B	0.16	1.61	0.08	400,000.00
C	4.53	45.30	2.27	11,350,000.00
D	0.40	4.00	0.20	1,000,000.00
Total	10.37	103.71	5.19	25,950,000.00
H_2O_2 criteria				
A	2.42	24.20	1.210	6,050,000.00
B	0.13	1.29	0.065	325,000.00
C	0.21	2.11	0.105	525,000.00
D	0.38	3.76	0.188	940,000.00
Total	3.14	31.36	1.568	7,840,000.00

potential in site D is probably underestimated since there were other tailing pools not sampled in our study. These pools contain around 1,191,105 t of potentially acid generating tailing, as informed by the Minas Gerais Environmental Agency (FEAM).

The AMD generation potential for Minas Gerais State is presented in table 8, but it should be kept in mind the limitations and constraints discussed above for each mine. The costs for neutralization with lime, which is the cheapest and most abundantly available neutralizing product, were estimated at US$ 5.00 t^{-1}. Considering this cost, AMD represents a potential cost of US$ 7.8 to 25.9 millions to neutralize acidity.

Jointly, these activities represent a potential to generate around 3.14 to 10.37 billions of m^3 of water at pH 2 or 31.4 to 103.7 billions of m^3 of water at pH 3. This, in turn, represents costs of US$ 7.8 and 25.9 millions for acidity neutralization with limestone. These quantities are probably underestimated because some mines were not included in the survey, and for other mines, surface samples may not represent the whole picture. A more reliable evaluation of the acid drainage potential at state level would require further studies. These studies must include a larger number of samples from mining operations not considered in this study. They should further consider the kinetics of the acid generation by simulated weathering methods.

CONCLUSIONS

1. The estimates of the AMD generation potential differ according to the adopted criteria. They are higher when calculated based on the total content of sulfides after "aqua régia" digestion than with the acidity potential (AP) measured after peroxide oxidation. The AP calculated from the total sulfide content is probably overestimated due the presence of other sulfides such as arsenopyrite, calcopyrite, sphalerite, and pentlandite, whose stoichiometry of acid generation differs from that of pyrite. On the other hand, the peroxide analysis probably underestimated AP due to incomplete sulfide oxidation.

2. The results identified four mining sites with potential to generate acid drainage in Minas Gerais.

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