

Impact of Mining Activities on Water Resources in the Vicinity of the Obuasi mine

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Abstract

Surface and groundwater samples within the catchment area of the Obuasi mine were analysed to assess the impact of mining activities on water resources. The concentration of Fe, Mn, Cu, Zn, Pb, Cd, Hg, As and selected major ions in water samples were analysed to assess their role in the contamination of both surface and ground water. The mineralogical composition of various mine spoil and rock samples was investigated by microprobe analysis to ascertain the possible sources of the metals in drainage and ground water. The hydrochemical analytical study, using standard methods, shows that streams in the study area have higher trace and major ions loading than ground water with iron and arsenic concentrations ranging from 0.025 mg/l to 17.19 mg/l and < 0.001 mg/l to 18.91 mg/l, respectively. Hydrochemical modeling of water types showed varied composition for both ground and surface water, but with strong indication of mixed waters from a variety of sources. The microprobe results showed that waste rocks and related mine spoil contain a variety of Fe, Cu, As, Sb, Zn and co-bearing sulphides with strong compositional variations, and account for the augmented levels of these metals in drainage proximal to mining and processing facilities. The probe results did not show Hg in mine spoil, and very high Hg values observed in the vicinity of areas of intense illegal small-scale mining are attributed to the use of this chemical by miners in gold amalgamation.

Introduction

The study area is within the mining lease of the Ashanti Goldfields (Obuasi) Limited, and situated 160 km northeast of Accra. The Obuasi mine has been in operation for the past 110 years and can be described as the single industrial hub of the Ghanaian economy. It has produced in excess of 30 million ounces of gold since its inception and accounts for over 60% of the total national gold production. Its inventory of global resources is estimated in the neighborhood of 80.8 million tons at 8.1 g/t (Gyapong & Amanor, 2003).

The mine has undergone extensive expansion and modernization in the last two decades resulting in the development of extensive open pit mines and increased underground mining operations boosted by the development of a mosaic of new shafts. There has also been modernization of the processing technology used in the mine, with the introduction of hydrometallurgy and bio-oxidation technologies and gradual phase-out of pyrometallurgical processing up to 2000, in a move to reduce environmental pollution. The area also has a long history of native mining. Artisanal mining has been recorded in the area as early as 1471 (Kesse, 1985). Currently, active artisanal mining is intense in the area, but conducted by illegal miners, since the entire area is covered by the concession of Ashanti Goldfields.

The development of extensive mining operations in an area that can be described as ecologically sensitive zone, covered by forested highlands rising up to 400 m above sea level in some places and well-developed drainage system would certainly give rise to environmental problems. The changes from pyrometallurgy to hydrometallurgy and bio-oxidation were aimed at minimizing some of these environmental problems associated with the mineralogy of the ore. Environmental monitoring data obtained from water quality, mineralogical and geochemical studies have been limited to the vicinity of these processing facilities and ore, respectively (Amonoo-Neiser & Busari, 1980; Jetuah, 1997; Carbo & Sarfo-Armah, 1997; Clement *et al.*, 1997).

There is paucity of literature on specific geological controls on natural and mine water and their impacts on water resources in the area. The paper examines the mineralogical assemblages

in mine spoil and rocks hosting toxic heavy metals as possible sources of these metals in drainage and ground water in the area, and assesses the impact of mining including illegal artisanal mining activities on water resources in the Obuasi township and its satellite communities (Fig.1).

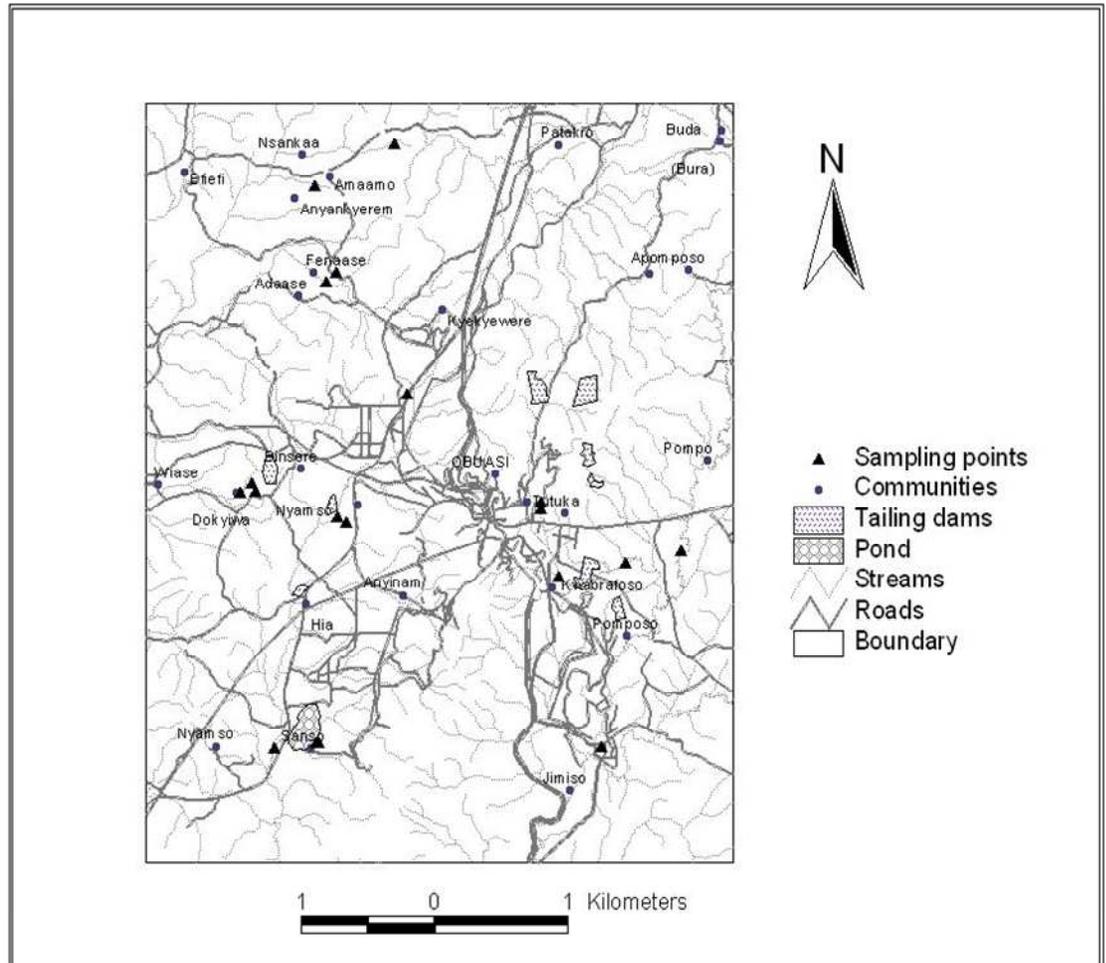


Figure 1: Map of Study Area showing sampling points.

Geological setting

The geology of the Obuasi mine has received considerable attention (Junner, 1932; Gyapong, 1980; Kesse, 1985; Bowell, 1993). The deposit is located in Birimian metavolcanics and metasedimentary rocks. Bedded and altered dark gray and black phyllite and sericite schist dominate the metasediments with quartz, sericite, and carbonates making up the bulk of mineralogy of these metasediments. The metavolcanics represent concordant flows within the metasedimentary pile (Hirdes & Leube, 1989) that are intruded by contemporaneous and post tectonic granitoids. The volcanic units are largely tholeiitic in character that have been subjected to greenschist metamorphism. Mineralogically, they are dominated by carbonate, chlorite, albite, sericite quartz, leucoxene and epidote.

Structurally, mineralisation conforms to a general strike of NNE-SSW. Multiple deformational events have produced pervasive shear zones, striking between north and NE, and dipping at fairly high angles on either side of the vertical plane. These zones acted as channels for gold laden

solutions (Gyapong, 1984). These multiple deformational regimes are believed to account for four distinct mineralization types at the mine: quartz vein mineralization, disseminated sulphides mineralization, granitoid mineralisation and supergene-enriched oxide ores (Gyapong & Amanor, 2003). It is the quartz veins and the oxide ores that are very amenable to mining and mercury amalgamation by illegal miners in the area.

Materials and methods

Two different media were sampled in the study: rock samples were taken from mainly mine spoil heaps to assess their sulphide mineralogy, principal custodians of heavy metals and water from streams, boreholes and hand-dug wells were collected to evaluate heavy metal status and other water quality parameters. A total of 30 samples from the different media were taken with the following distribution: five rock samples and 25 water samples comprising 12 from boreholes, 10 from streams and three from hand-dug wells.

The collection, preservation, storage and preparation protocols of water samples followed those outlined in APHA (1998) and elaborated by Eppinger *et al.* (2000) for major ion and trace element determination. For water sampling, polyethylene bottles were rinsed three times with the water to be sampled prior to sampling. The analyses were performed at the Water Research Institute of the Council for Scientific and Industrial Research, and followed standard methods.

Rock samples were examined in hand specimens and appropriate areas of interest marked for polished thin section for mineralogical and chemical studies using transmitted and reflected light microscopy and electron microprobe analysis, respectively. Phase and textural relations among sulphides, carbonates and silicates were noted during microscopy and electron microprobe examination. The analysis was conducted at the Geological Institute of the University of Copenhagen, Denmark, using a JOEL JXA- 8200 WD/ED Supermicrobe combined micro analyzer operating at 20 KeV with 10 µm beam resolution and wave dispersion (WD) length of 11 mm. Each spectrum was acquired in 20 seconds. Standard reference materials were used to calibrate the instrument for quantitative analysis of sulphides, carbonates and silicates.

Results and discussion

The results demonstrate significant variation in the concentration of the determined metals in water samples. Microprobe investigations revealed varied sulphide mineralogical assemblages with strong compositional variation arising from the incorporation of potentially toxic trace metals which also had strong finger prints in drainage waters.

Water

The hydrochemical analytical results show that streams in the study area are more polluted than groundwater. Groundwater is generally benign with only iron and arsenic values exceeding the maximum permissible WHO guide values in one sample in the case of iron and in four samples in the case of arsenic. Concentrations of iron and arsenic in groundwater range from below detection to 15.34 mg/l and 0.801 mg/l, respectively (Table 1). Concentrations of the measured parameters in water from streams are much higher than in groundwater and are several orders of magnitude above the WHO permissible maximum guidelines for these parameters in water except for zinc and copper.

TABLE 1
Water quality parameter status in groundwater water in (mg/l) except otherwise stated

Parameter	Mean	Median	Standard deviation	Min	Max	WHO max. guide value
Fe	1.343	0.044	3.938	0.019	15.340	0.3

Mn	0.120	0.103	0.106	0.001	0.329	0.5
Cu	0.025	0.020	0.023	0.001	0.094	2
Ni	0.013	0.011	0.012	0.002	0.046	0.02
Zn	0.042	0.028	0.039	0.004	0.127	3
Pb	0.016	0.001	0.026	0.000	0.096	0.01
Cd	0.002	0.002	0.002	0.002	0.009	0.003
Hg	0.004	0.001	0.004	0.001	0.009	0.001
As	0.082	0.009	0.211	0.009	0.801	0.01
pH	4.969	5.070	0.608	3.700	5.620	6.5–8.5
Conductivity (µS/cm)	149	147	86	51	344	
Total alkalinity	34	21	38	0	128	
Ca	8.540	7.200	7.345	0.800	30.500	200
Cl	8.727	5.860	10.141	0.190	36.700	250
Na	12.380	11.100	6.605	3.300	25.700	200
K	0.207	0.010	0.338	0.010	1.100	30
NO ₃	8.065	0.700	20.616	0.019	80.300	10
PO ₄	0.206	0.040	0.317	0.014	1.030	
SO ₄	1.211	1.380	0.835	0.040	2.460	400
F	0.070	0.070	0.040	0.020	0.190	1.5
SiO ₂		33.180	29.500	11.926	12.300	50.500
Mg	5.467	5.300	2.868	0.500	9.500	150
HCO ₃		64.793	65.000	33.811	0.000	126.900
TSS		7.275	0.500	17.469	0.090	66.000
TDS	97.173	95.600	55.740	33.300	223.600	1000
Turbidity	3.121	1.000	3.210	0.630	10.000	5

Number of samples = 13

Asernic values are above the WHO guide values in all streams including The Fena at Adaase, Hia No. 2 and Faaman, all upstream of mining and processing facilities. However, the highest concentration of arsenic in streams were recorded immediate down-stream of mining and processing facilities. Iron values in streams range from 0.0259 mg/l at Adaase to 17.19 mg/l at Kwabrafoso while arsenic ranged from < 0.001 mg/l at Adaase to 18.91 mg/l at Kwabrafoso (Table 2). The arsenic concentration in streams within the vicinity of mine facilities in the study area of up to 18.91 mg/l is considerably higher than the average range of As in typical arsenopyrite bearing gold ore, globally estimated between several µg/l to 100 µg/l (Dinelli & Tateo, 2001). Major ion concentrations in streams exhibit similar patterns as trace ions discussed above.

TABLE 2
Water quality parameter status in streams (mg/l)

Parameter	Mean	Median	Standard deviation	Min.	Max.	WHO max. guide value
Fe	5.032	3.642	5.258	0.259	17.190	0.3
Mn	0.758	0.464	0.777	0.146	2.584	0.5
Cu	0.023	0.020	0.024	0.000	0.086	2
Ni	0.025	0.015	0.022	0.003	0.058	0.02
Zn	0.034	0.022	0.035	0.003	0.120	3
Pb	0.014	0.003	0.021	0.001	0.057	0.01
Cd	0.002	0.002	0.000	0.002	0.002	0.003
Hg	0.008	0.009	0.005	0.001	0.018	0.001
As	3.137	0.291	5.903	0.009	18.910	0.01
pH	6.678	6.665	1.041	4.660	8.330	6.5–8.5
Cond (µS/cm)	389.000	376.500	233.049	126.000	847.000	
Tot. alkalinity	24.710	0.000	33.431	0.000	87.000	

Ca	26.360	15.600	23.454	8.000	75.400	200
Cl	14.560	11.600	7.148	7.780	27.000	250
Na	24.340	16.950	18.121	5.900	60.500	200
K	10.940	9.550	7.974	2.300	27.000	30
NO ₃	0.144	0.035	0.286	0.010	0.940	10
PO ₄	0.544	0.090	0.904	0.014	2.800	
SO ₄	76.121	59.550	71.452	3.000	240.000	400
F	0.053	0.050	0.024	0.020	0.100	1.5
SiO ₂	21.140	21.350	4.021	13.100	26.600	
Mg	11.930	8.500	10.988	2.400	33.400	150
HCO ₃	112.120	111.550	68.054	19.500	258.600	
TSS	344.550	66.500	866.406	1.500	2799.000	
TDS	252.870	244.750	151.488	81.900	550.600	1000
Turbidity	106.925	41.500	154.230	3.000	501.000	5

Number of samples = 10

Elevated values of Mg, Ca, SO₄, HCO₃ are observed in samples from streams immediately down stream of mining and processing facilities at Kwabrafoso, Binsere, Dokyiwa and Sansu. The strong spatial variation in the concentration of measured parameters is reflected in the standard deviations presented in Tables 1 and 2.

Generally, major ions from stream samples show strong moderate to positive correlation with As, Mn, Cu, Ni, and Zn. According to Zhu *et al.* (2003), such positive correlation of arsenic and heavy metals with major ions provide evidence that arsenic and these trace ions are likely derived locally from the water-mineralized rock interaction. This suggests that they are products of dissolution of host minerals occurring together. As pointed out by Plumlee *et al.* (1999), the concentration of individual elements in drainage waters, in part, reflect the elements' abundance in the geological units being drained. Price & Errington (1998) also confirmed that such high concentrations of trace ions such as Mn, Cu, Ni, Zn and As in neutral pH drainage, as exhibited in this study, results from localized acid generating sources.

Elevated metal leaching is usually associated with acidic drainage due to high metal solubility and sulphide weathering rates under acidic conditions. Alkaline earth carbonates such as calcite, dolomite, ankerite and magnesite typically react to produce elevated Ca, Mg and HCO₃- concentrations. The elevated trace ions, sulphate concentrations, total dissolved solids and electrical conductivity within the vicinity of mining facilities and the very strong correlation among these parameters are strong indication of water quality degradation related to mining (Bell *et al.*, 2002).

The defining impact of these elevated major ions on the waters in the area is amplified in the Piper trilinear plot of major ions in groundwater and surface water in the study area (Piper, 1944) (Fig. 2). The exact chemical composition of these waters modeled from Aqua Chem 3.70 is presented in Table 3. The waters in the area are dominated by Ca²⁺-Mg²⁺-Na⁺-HCO₃⁻ and Ca²⁺-Mg²⁺-Na⁺-HCO₃⁻-SO₄²⁻ dominant waters, with variations in the preponderance of the Mg, Ca and Na ions. The overall chemical composition of the water reflects the geology and mineral assemblages in the area. Such a menu of mixed ions in stream water as presented in Table 3 is certainly an indication of mixing of water, and, according to Hem (1985), that would likely be produced by the dissolution of silicates, sulphides and carbonates.

TABLE 3
Chemical composition of waters from the study area

Water source	Community	Water type
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Borehole #1	Adaasi	Mg-Ca-SO ₄
Borehole #2	Adaasi	Na-Mg-Ca-HCO ₃
Borehole#1	Akatakyyieso	Na-Mg-Ca-HCO ₃
Borehole #2	Akatakyyieso	Na-Mg-Ca-HCO ₃
Borehole	Dokyiwa	Mg-HCO ₃
Borehole #1	New Bidiem	Ca-Na-Mg-HCO ₃
Borehole #2	New Bidiem	Mg-Na-Ca-HCO ₃
Borehole #1	Ntonsua	Na-Mg-Ca-HCO ₃
Borehole #2	Ntonsua	Na-HCO ₃
Borehole	Amamon	Na-Ca-Mg
Hand dug well	Hia #1	Na-Ca-HCO ₃
Hand dug well	Hia #2	Ca-Na-Mg-HCO ₃ -C
Hand dug well	Fenaaso	Na-K-Ca-HCO ₃ -SO ₄
River Fena	Fenaaso	Na-K-Ca-HCO ₃
River Fena	Hia #2	Na-Ca-Cl-HCO ₃
River Jimi	Jimiso	Ca-Mg-Na-HCO ₃ -C
R. Kwabrafo	Kwabrafoso	Ca-Mg-SO ₄ -HCO ₃
R. Kwaab	Kwabrafoso	Ca-Mg-Cl-HCO ₃
R. Supu	Ntonsua	Na-Ca-Mg-HCO ₃ .SO ₄
R. Fena	Adaasi	Na-Ca-Mg-HCO ₃
R. Kwami	Dokyiwa	Na-Ca- SO ₄ -HCO ₃
River San	Sansu	Ca-Mg-HCO ₃ -SO ₄

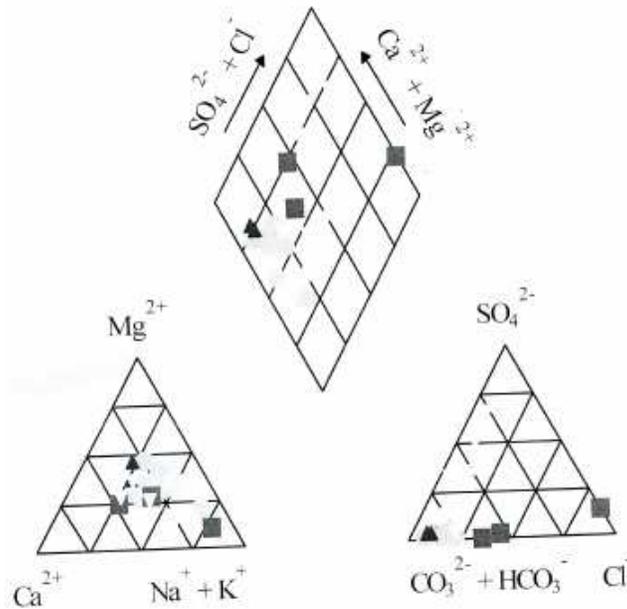


Fig. 2. Piper trilinear plot of waters in the study area

The Mg and Ca ions are likely derived from carbonates, mainly siderite and ferroan dolomite, which form a significant component of the mineralogy of the rocks in the area (Hirdes & Leube, 1989). However, the Mg and Ca, together with Na ions, could also have come from the dissolution of the silicates. HCO₃⁻ ions, could come from reduction of sulphate (from oxidation of

sulphides) and root zone material by microbial activities. The area has substantial sulphides, especially pyrite and arsenopyrite, the oxidation of which could contribute SO_4^{2-} ions to the waters. The chloride could be from anthropogenic sources and the intrusive rocks typified by granitoids in the area. The carbon is most likely from the graphic schist metasedimentary sequences. In fact, Gyapong (1980) states that graphic schist at the Ashanti mines contain, on average, 4% elemental carbon.

Evidence of water degradation due to mining is from the fact that while there is augmented concentrations of major and trace ions in water samples from Kwabrafoso, Tutuka, Dokyiwa and Sansu, all proximal to mine facilities, there is attenuation of the concentration of the parameters in streams further away from, and upstream of mining and processing facilities. The concentration of major and trace ions in samples from Amaamo, Fenaase and Adaase, all upstream of mining and processing facilities, are highly subdued and rarely exceed the WHO guide values of the measured ions in waters from these communities. Similarly, a sample from the Jimi river, which also takes drainage from the other streams distal to mining activities, are relatively low due largely to dilution and sequestering of these elements in sediments.

Sources of metals in waters

The spatial correlation between augmented metal concentrations, and mining and processing facilities, and mine spoil sites suggest that mine waste sites constituent sources of these metals in drainage water. Microprobe analysis of rock samples taken from rock waste dumps and exposed outcrops in the area show that the waste rocks contain a variety of base metal and metalloid-bearing sulphides, together with carbonates (calcite, dolomite, ankerite, siderite), silicates and oxides. The analysis showed that sulphides content in waste rock samples ranged between 0.01% and 3.86% while carbonates ranged from 0.01% to 15%. This study put emphasis on the analysis of sulphides because they constitute the principal custodians of the toxic metals analysed in water samples. The probe results show that sulphides exhibit strong compositional variation defined by their relative trace element content. Fe, As, Cu, Ni, Zn, Sb and Co-bearing varieties constitute the dominant sulphides. Table 4 shows the compositional variations of pyrite, arsenopyrite, chalcopyrite, sphalerite, ullmannite and gersdorffite in probed mineral grains in rock samples taken from mine spoil.

From the menu of trace metals and major ions observed in water and the compositional complexity of the observed sulphides in the rocks, it can be deduced that the weathering of these sulphide-bearing rocks, greatly facilitated by mining, accounts for the elevated ions in the water in the vicinity of the mining and processing facilities. According to Larocque & Rasmussen (1998), mine spoil, especially tailings environments are the sites of metal flux from the geosphere to the hydrosphere through dissolution of minerals. The exposure of rock strata to the atmosphere (air and water) promotes oxidation of the sulphides, leading to the discharge of the contained metals into local drainage. According to Plumlee *et al.* (1999), schematically, the following reactions can take place to generate these ions under typical surface weathering conditions:

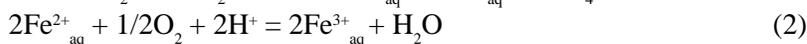
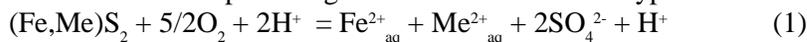


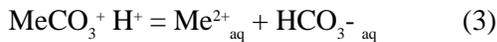
TABLE 4
Results of microprobe analyses (in atomic %) of various sulphides in rock samples

<i>Mineral</i>	<i>S</i>	<i>Mn</i>	<i>Ni</i>	<i>As</i>	<i>Fe</i>	<i>Sb</i>	<i>Zn</i>	<i>Co</i>	<i>Cu</i>	<i>Total</i>	<i>n^l</i>
<i>Sphalerite</i>											
Min (Cu)	46.06	0.10	-	0.04	9.68	-	43.89	-	-	98.77	
Max (Cu)	50.20	0.01	0.02	0.03	2.75	-	46.97	-	0.03	100.01	12
Average	51.83	0.02	0.01	0.02	2.83	-	44.11	-	1.05	99.87	

<i>Chalcopyrite</i>											
Min (Cu)	44.13	0.01	–	0.03	5.03	13.98	2.68	–	33.68	99.44	
Max (Cu)	44.27	0.03	–	0.02	5.20	13.94	2.68	–	33.93	100.07	11
Average	44.41	0.01	0.01	0.13	4.82	13.99	2.72	–	33.83	99.92	
<i>Ullmannite</i>											
Min (Ni)	32.32	0.02	32.53	6.22	1.21	27.32	0.02	0.10	0.50	99.62	
Max (Ni)	31.67	0.07	32.79	3.08	1.69	30.41	0.05	–	0.23	99.97	7
Average	32.55	0.05	32.54	0.46	1.31	32.95	0.04	0.01	0.18	100.09	
<i>Cobaltite</i>											
Min (Co)	34.91	0.02	7.04	32.48	9.51	–	–	13.18	2.85	99.99	
Max (Co)	36.11	0.09	4.93	28.83	7.90	0.03	–	21.62	0.47	99.98	9
Average	43.37	0.08	6.34	23.30	10.43	0.26	–	15.90	0.33	100.01	
<i>Gersdorffite</i>											
Min (As)	34.37	0.01	29.68	29.48	1.89	4.40	–	0.01	0.15	99.99	
Max (As)	34.34	0.05	19.78	32.90	4.64	0.28	–	7.84	0.20	99.97	10
Average	33.42	0.06	29.78	31.35	1.52	1.67	0.04	1.78	0.37	99.99	
<i>Pyrite</i>											
Min (Fe)	66.69	–	0.04	–	33.24	–	0.01	–	0.02	100.00	
Max (Fe)	66.30	–	0.02	0.03	33.67	–	0.02	–	0.02	100.06	14
Average	66.50	0.01	0.03	0.02	33.45	–	0.1	–	0.01	100.11	
<i>Arsenopyrite</i>											
Min (As)	35.39	0.01	0.04	31.64	32.52	–	–	0.39	–	99.99	
Max (As)	24.18	0.01	0.07	38.31	34.41	–	–	2.81	–	99.79	12
Average	34.95	0.01	0.05	31.74	32.80	–	–	0.41	–	99.99	

n – Number of electron microprobe analysis

(Fe,Me)S₂ could be pyrite, chalcopyrite, bornite or arsenopyrite. The oxidation of Fe²⁺ to Fe³⁺ would enable the aggressive oxidation of other metal sulphides with metal to sulphide ratio less than 1, which would normally not be affected by the oxidation reaction in equation 1 (Evangelou, 1995). This would have been the most likely dissolution mechanisms for sphalerite, ullmannite and gersdorffite minerals identified in this study. The carbonate minerals present will usually react with the acid solution generated from equations 1 and 2 according to the generalized neutralization reaction:



MeCO₃ could be calcite, dolomite, ankerite, siderite or magnesite.

Both acid producing and consuming reactions as schematized above would typically generate constituents such as the metals, sulphate and bicarbonates into solution, and transform others into stable constituents in sediments, as observed in the waters from the study site. Thus, these oxidation and neutralization processes, together with other possible weathering reactions involving silicates and oxides within the mine spoil would generate the menu of trace and major ions in the drainage waters while similar reactions from wall rock/water interactions and seepage will account for high level of metals encountered in some of the boreholes.

Conclusion

The results show that past and present large scale and illegal small-scale mining activities have affected water resources in Obuasi and its satellite communities. Stream water is significantly polluted by As, Hg, Fe, and, to some extent, Cu, Ni and Zn. Groundwater is quite benign and rarely exceeded the WHO guide values for portable water with respect to major and trace element concentration. Microprobe mapping of sulphide grains in rock samples showed a variety of Cu, As, Ni and Zn bearing sulphides as possible sources of augmented concentrations of these pollutants in water. The strong correlation among Cu, As, Ni and Zn in both water and the significant occurrence of the respective sulphides in the country rock and waste rocks confirm that the weathering of these materials provided these pollutants in the water and sediments.

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