

ACID MINE DRAINAGE AND HEAVY METALS CONTAMINATION OF SURFACE WATER AND SOIL IN SOUTHWEST BURKINA FASO–WEST AFRICA

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ABSTRACT

In Southwest Burkina Faso, a decade of gold mining at Poura left large stockpiles of mine wastes. Once exposed to the atmosphere and water, these wastes may be oxidized leading to generation of a highly acidic effluent known as Acid Mine Drainage containing a series of potentially toxic dissolved metals. In the present study, surface water, groundwater, soil and mine waste samples were collected around the Poura Gold mine, to assess a possible release of heavy metals in the surrounding environment. The low pH values (~2.23) and high heavy metal contents measured in some surface water originating from oxidized zones of the waste stockpiles attested that the site has been subject to the acid mine drainage. Furthermore, geo-accumulation index of soil and mine waste samples indicated that the surrounding soils are contaminated by heavy metals. That is, it has been established that the soils were moderately contaminated by arsenic, cobalt, chromium, copper, lead and nickel, whereas they are moderately to strongly contaminated by arsenic. Likewise, mine wastes samples were moderately contaminated by arsenic, cobalt, chromium, copper, lead, zinc and nickel in one hand and moderately to strongly contaminated by arsenic, copper and lead in the other hand. Arsenic is the most polluting element and induces high contamination of the mine wastes (strongly contaminated: Igeo class 4 with Igeo value ranging from 3 to 4). The source of these heavy metals is sulfides e.g. arsenopyrite: FeAsS , chalcopyrite: CuFeS , galena: PbS encountered in the mineralized host rocks at Poura which was operated and has produced several tons of mine wastes and waste rocks stored since many years.

Keywords: Mine wastes, Heavy metals, Contamination, Environment, Burkina Faso.

INTRODUCTION

Due to the high mineral and metal demand of emerging economies such as India and China, the prices of these commodities have increased on the international market, leading to intensive mining worldwide. Burkina Faso, a landlocked country, has been long considered as a least developed backward agricultural country that may benefit from the "mining boom". Since 2010, the country has become the fourth largest African gold producing country after South Africa, Ghana and Mali. Nowadays Burkina Faso has seven active gold mines (Taparko, Essakane, Mana, Youga, Inata, Kalsaka, Sabcé).

The Poura Gold mine (Figure 1) was the first industrial gold mine of the country. The mine was operated from 1985 to 1999 by the state owned mining company "Société de Recherches Minières du Burkina Faso (SOREMIB)". During this period, Poura Gold mine produced approximately 15 tons of gold. In 2012 the mine was reopened by Newmont, an American mining company, but the activities are currently limited to exploration and prospection. The previous mining (i.e., 1985-1999) has generated several tons of mine wastes which are still piled up on the site.

These mine wastes consist of overburden, waste rock dumps, tailings and usually various sulfide and iron minerals. In the nature the interaction between these minerals and oxygen

and/or water lead to their oxidation, a process known as acid rock drainage (ARD). However, an exacerbated ARD through mining is known as acid mine drainage (AMD).

AMD is characterized (Kawatra and Natarajan, 2001) by high acidity (low pH) and high concentrations of sulfate and metals and metalloids such as iron (Fe), manganese (Mn), aluminum (Al), zinc (Zn), copper (Cu), nickel (Ni), lead (Pb), cadmium (Cd) and arsenic (As). As a result, AMD represents, by far, the most serious threat to the ecosystem adjacent to mining sites. Thus, AMD acidifies the receiving environment through a release of sulfuric acid, and also maintains in solution highly reactive and toxic metals (US-EPA, 2000; Naicher 2003; Galvez-Cloutier and Lefrancois 2005). Thus, AMD enhances the mobility and bioavailability of potentially toxic metals in the ecosystem.

The main metals released into the environment due to mining are: Fe, Mn, Pb, Zn, Cd, Cr and Ni. Increased solubilization of these metals following AMD generation can enter food web, and pose serious threats to human health through consumption, for example, of contaminated seafood. In humans, the metals are stored in most soft tissues, particularly the liver and kidneys as well as in the bone, Collon (2003). The ingested metals are therefore bio-accumulative and non-biodegradable in human body, and thus highly toxic even at very low doses (trace amounts).

The aim of this paper is to assess the spread of potentially harmful elements (PHE), e.g. heavy metals associated to mine wastes and tailings, and its impacts on the environment.



Figure 1: Geological map of Burkina Faso with the location of Poura gold mine.

Acid Mine Drainage (AMD)

By definition, acid mine drainage is an effluent produced during mining or after the mine closure which physico-chemical characteristics differ from the original water (Collon, 2003).

In the deposits and in particular metalliferous deposits, minerals are usually associated with sulfur or iron minerals (pyrite, chalcopyrite, arsenopyrite, galena, sphalerite, pyrrhotite, covellite). Consequently, these sulfide minerals are found in tailings or waste rock piles. Exposure of tailings to air and water leads to sulfate and iron oxidation and production of acid mine drainage known as AMD. The kinetics of this oxidation reaction is enhanced in the presence of *thiobacillus ferrooxidans* bacteria, that can speed up the reaction rate about 105 times compared to abiotic reaction.

The acidification will impact the release of metals from various minerals. An orange-brown color of insoluble Fe(OH)₃ usually characterizes this acidic drainage.

Assuming the presence of pyrite in tailings (Kleinman et al., 1981; Aubertin et al., 2002a; Bussière et al., 2005), interaction between tailing seeping or highly acidic process waters and a receiving environment (e.g., surface water) with a pH close to neutral (5 < pH < 7), oxygen will directly oxidize pyrite as illustrated in reaction 1.



Ferrous iron, released from the oxidation of pyrites, can be oxidized to ferric iron according to the following reaction:



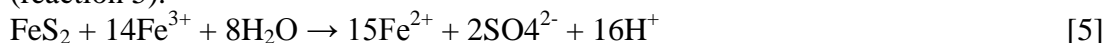
At relatively high pH (pH > 4), the ferric iron precipitates as ferric hydroxide releasing more acid in water (reaction 3).



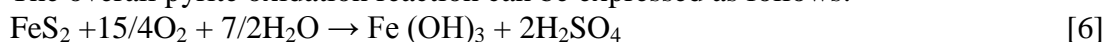
The ferrous iron can also be precipitated as iron hydroxide and produce acid as shown in reaction 4.



When the pH is sufficiently low (pH < 4), ferric iron remains in solution, and thus playing the role of a highly reactive oxidant (the so-called indirect reaction). The indirect oxidation of pyrite produces more protons, and thus exacerbates acidification of the receiving environment (reaction 5).



The overall pyrite oxidation reaction can be expressed as follows:



These equations show that the oxidation of one mole of pyrite produces two moles of sulfuric acid in the environment.

METHODOLOGY

Samples of surface water, groundwater (hand-pumped boreholes and wells), soil and mine wastes were collected at Poura old gold mine. Water concerned surface water and groundwater to assess their chemical parameters. The pH and water temperature have been measured in the field; geographic coordinates of sampling site have been recorded. For ground water, the depth (of the well) is recorded.

Each sample of mine wastes and soil is a composite of three sub-samples collected from sampling sites located at the distance of 10-20 m from each other. About, 3 kg have been dried, sieved and homogenized. The < 2mm fraction (about 5g), have been taken for analysis.

All samples (water, mine wastes, and soil) were shipped to Johannesburg (South Africa) to the laboratory "Acmelabs" for analysis.

Water samples have been the subject of the determination of F, pH, conductivity, alkalinity and Hg.

Samples of mine waste, and soil were subjected to aqua regia digestion and a full suite of 36 elements have been analyzed.

RESULTS

Sampling

All collected samples are reported in Figure 2. A total of 10 groundwater samples, 14 of surface water, 16 of soil and 11 of mine wastes were collected.

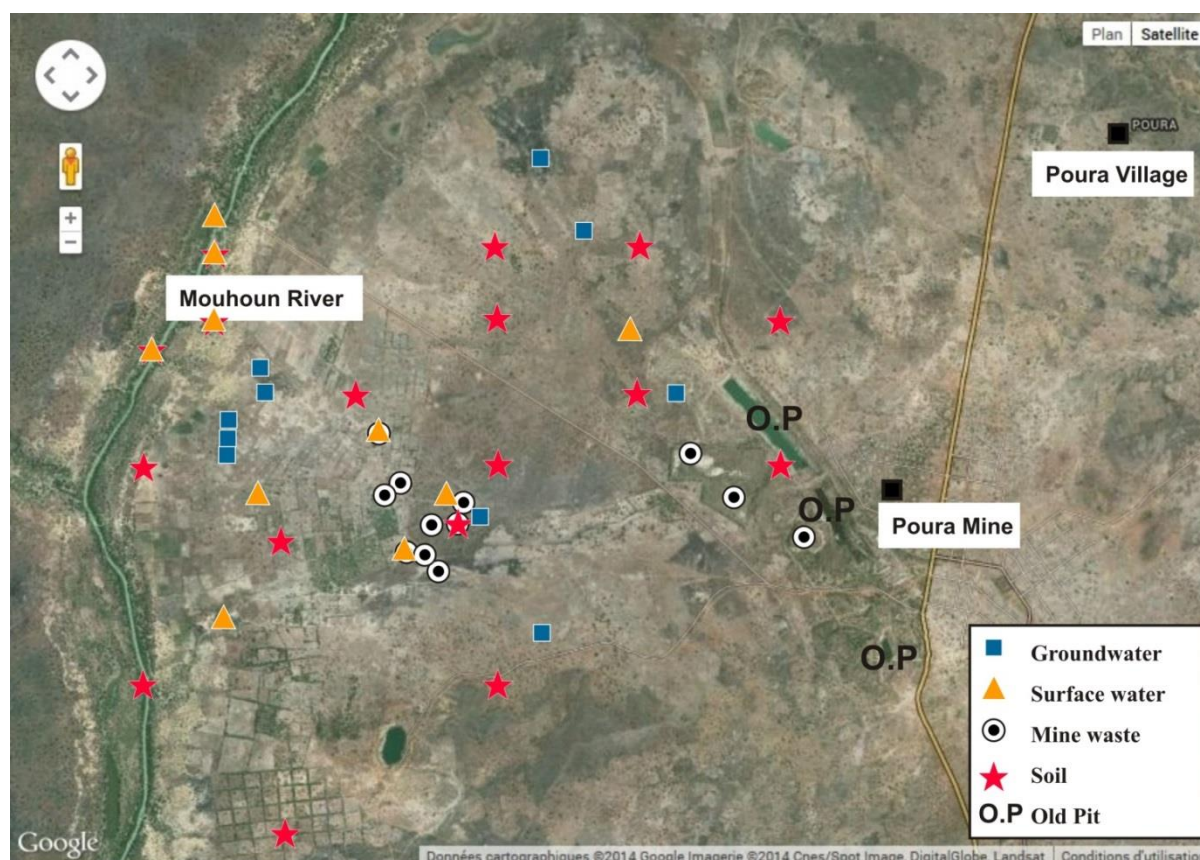


Figure 2: Location of sampling sites on the satellite map (Google imaging © 2014)

Groundwater and surface water

Results of chemical analyses of the groundwater and surface water are given in Tables 1a and 1b.

Table 1a: Chemical analyses of groundwater

Physical parameters					Miscellaneous inorganics (mg/l)				
Sample	Depth (m)	Temperature (°C)	Conductivity (μ S/cm)	pH	Fluoride	Alkalinity Total CaCO ₃	Bicarbonate HCO ₃	Carbonate CO ₃	Hydroxide OH
GW1	*HPB	31.50	340	8.45	0.190	189	221	4.82	<0.50
GW2	*HPB	32.30	239	8.35	0.120	133	158	2.22	<0.50
GW3	25	23.40	157	8.02	0.096	78.6	95.9	<0.50	<0.50
GW4	*HPB	30.70	357	8.39	0.250	197	232	4.03	<0.50
GW5	30	28.60	169	7.73	0.098	58.9	71.9	<0.50	<0.50
GW6	*HPB	30.80	365	8.37	0.240	155	184	2.87	<0.50
GW7	*HPB	30.80	339	8.38	0.200	145	170	3.04	<0.50
GW8	*HPB	31.00	455	8.32	0.063	193	230	2.42	<0.50
GW9	10	29.40	153	7.49	0.045	17.8	21.7	<0.50	<0.50
GW10	*HPB	28.40	456	8.67	0.130	244	271	13.10	<0.50

*HPB: Hand-pumped borehole

Table 1b: Chemical analyses of surface water

Physical parameters				Miscellaneous inorganics (mg/l)				
Sample	Temperature (°C)	Conductivity (μ S/cm)	pH	Fluoride	Alkalinity Total CaCO ₃	Bicarbonate HCO ₃	Carbonate CO ₃	Hydroxide OH
SW1	28.3	234	8.03	0.076	60.70	74.10	<0.50	<0.50
SW2	29.1	233	7.88	0.065	61.80	75.40	<0.50	<0.50
SW3	29.0	454	8.33	0.380	165	197	2.12	<0.50
SW4	27.6	60.4	6.61	0.064	8.29	10.10	<0.50	<0.50
SW5	34.2	146	8.07	0.110	70.00	85.40	<0.50	<0.50
SW6	28.3	45.6	7.44	0.058	16.30	19.80	<0.50	<0.50
SW7	32.2	45.7	7.54	0.072	16.70	20.30	<0.50	<0.50
SW8	29.3	225	7.95	0.059	59.50	72.60	<0.50	<0.50
SW9	28.6	287	8.13	0.670	150	183	<0.50	<0.50
SW10	27.9	624	8.51	0.400	290	336	8.99	<0.50
SW11	30.2	112	8.06	0.090	47.10	57.50	<0.50	<0.50
SW12	27.9	556	8.27	0.160	191	233	<0.50	<0.50
SW13	34.2	8810	2.23	0.027	<0.50	<0.50	<0.50	<0.50
SW14	32.2	48.0	7.23	0.076	15.50	18.90	<0.50	<0.50

Mine wastes and soil

The contents of some potentially harmful elements are shown in Table 2a and 2b. This table shows for arsenic, copper, nickel, lead and zinc relatively much higher contents in the mine wastes than in soils. Concentrations in mine wastes are: arsenic (4 to more than 10000 ppm), lead (2 to 1339.6 ppm), zinc (14 to 604 ppm), copper (7 to 534.8 ppm), cobalt (3 to 40 ppm), chromium (5 to 304 ppm), nickel (3 to 101.3) and cadmium (0.1 to 5 ppm). These contents in the soil are: arsenic (0.5 to 335.2 ppm), lead (3.8 to 49 ppm), zinc (7 to 130 ppm), copper (7 to 49.7 ppm), cobalt (4 to 35.8 ppm), and chromium (41 to 299 ppm), nickel (6 to 133.6 ppm) and cadmium (for the most less than the detection limit).

Table 2a: Contents of some potentially harmful elements in the mine waste samples

Element	As	Cd	Co	Cr	Cu	Pb	Zn	Ni	Hg	Fe
Unit	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	%
*LOD	0.5	0.1	0.1	1	0.1	0.1	1	0.1	0.01	0.01
W1	198.6	<0.1	3.4	5	7.7	21.9	21	5.8	0.24	0.70
W2	4.2	<0.1	39.0	87	80.9	2.3	84	68.3	<0.01	7.23
W3	563.7	0.1	35.6	39	41.6	11.9	69	47.4	0.05	3.37
W4	44.0	<0.1	4.7	14	17.8	1.3	14	3.2	<0.01	1.50
W5	4025.5	5.2	38.1	70	534.8	948.0	588	75.0	2.25	5.12
W6	549.8	<0.1	6.3	18	11.4	10.9	24	10.9	0.04	1.92
W7	151.5	<0.1	38.5	64	44.3	4.9	42	33.8	0.09	3.75
W8	141.8	<0.1	19.7	10	26.6	2.6	23	13.8	0.06	1.84
W9	309.6	1.7	28.7	304	253.8	804.0	604	101.3	0.26	12.88
W10	>10000.0	0.9	24.4	15	251.3	1339.6	107	60.2	4.08	9.24
W11	>10000.0	2.8	40.0	24	329.1	1069.8	364	83.3	3.68	10.97

*LOD: Limit of detection

Table 2b: Contents of some potentially harmful elements in the soil samples

Element	As	Cd	Co	Cr	Cu	Pb	Zn	Ni	Hg	Fe
Unit	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	PPM	%
*LOD	0.5	0.1	0.1	1	0.1	0.1	1	0.1	0.01	0.01
S1	1.3	<0.1	16.3	52	23.7	11.8	28	24.4	<0.01	2.92
S2	335.2	0.2	35.8	51	49.7	49.0	130	28.7	1.04	4.36
S3	9.9	<0.1	16.2	83	29.0	4.4	20	36.6	<0.01	3.37
S4	7.3	<0.1	25.8	141	27.1	5.6	34	74.6	0.01	3.86
S5	0.5	<0.1	4.8	25	7.6	6.8	7	6.6	<0.01	1.37
S6	3.6	<0.1	16.8	67	17.7	4.6	16	36.8	<0.01	2.23
S7	20.8	<0.1	17.9	55	19.0	4.9	11	11.7	0.02	2.38
S8	11.5	<0.1	22.0	299	23.8	3.8	21	133.6	0.01	3.63
S9	64.2	<0.1	24.6	70	31.5	16.2	73	21.4	0.84	4.16
S10	33.9	<0.1	20.3	50	23.9	4.6	35	25.2	0.05	3.52
S11	105.6	<0.1	30.7	283	42.0	30.2	47	22.5	1.18	12.89
S12	4.5	<0.1	16.6	103	18.1	4.8	17	30.8	<0.01	2.55
S13	19.0	<0.1	18.5	41	18.9	4.9	12	14.8	<0.01	2.17
S14	5.2	<0.1	14.1	57	11.6	5.6	15	12.1	0.02	2.92
S15	4.5	<0.1	12.2	43	14.3	4.1	13	16.7	<0.01	2.67
SNC1	17.7	<0.1	20.0	70	15.7	5.9	13	15.2	<0.01	2.43

*LOD: Limit of detection

DISCUSSION

All samples were collected in August (rainy season), which justifies the relatively high temperatures of water samples. Ground water is characterized by a pH close to neutrality (7.49-8.67) and relatively low conductivity values compared to the surface water (153-456 $\mu\text{S}/\text{cm}$). The surface water samples SW4 and SW13 show lower values of pH which are respectively 6.61 and 2.23. Sample SW13 with high conductivity (8810 $\mu\text{S}/\text{cm}$) and high acidity (low pH) confirms the presence of AMD resulting from the oxidation of tailings stored there. These values indicate that oxidation is local and very advanced in that the pH value is below the minimum 6.5 required for the protection of aquatic life and even below the acute toxicity of 5.0 (Berryman et al. 2003). According to the standards in force in Burkina Faso guideline values for fluoride are 0.07 to 1.5 mg/l. Concentrations of fluoride are higher in groundwater than in surface water. However, these values are consistent with the guideline values.

The alkalinity values are highly variable from one sample to another, and are higher in groundwater than in surface water. The acidification of SW13 is confirmed by its alkalinity which is less than the detection limit (0.50 mg /l CaCO₃). According to the "Ministère du développement durable, de l'environnement, de la faune et des parcs" (MDDEFP, 2013) the sensitivity of a medium to the acidification varies with alkalinity: high sensitivity, alkalinity < 10 mg /l CaCO₃; mean sensitivity, alkalinity ranges from 10 to 20 mg /l CaCO₃; low sensitivity alkalinity > 20 mg /l CaCO₃. The anions HCO₃⁻, CO₃²⁻ and OH⁻ have also been analyzed. Bicarbonate, carbonate and hydroxide form alkalinity, however, natural waters usually contain no carbonate or hydroxide.

The results given in Tables 2a and 2b show that the concentrations of various analyzed elements are higher in mine tailings than in soils. This is due to the mineralogy of the host rocks of the mineralization. Indeed, at Poura geology comprise mainly volcanic rocks (andesite-dacite), volcano-sedimentary (tuffs, agglomerates) and detrital sedimentary rocks (pelitic to conglomerate rocks) which are intruded by mafic to felsic intrusions (granites gabbroic). Gold is associated with quartz veins whose cracks are filled by sulfides: pyrite (FeS), arsenopyrite (FeAsS), sphalerite (ZnS), galena (PbS), chalcopyrite (CuFeS). High levels in some soil samples (arsenic: S2, S11; lead: S2 and zinc: S2) would come from contamination through leaching, solubilization (due to the decline in pH) and migration of elements from tailings stockpiles. This means enrichment for these elements. Sampling site S2 is the most contaminated and mainly by arsenic, lead and zinc.

For soils there are no guideline values from Burkina Faso. But according to Canadian soil quality guidelines for the protection of environmental and human health (Canada, ATSDR, 2005), and taking into account the fact that these soils used for agriculture, some sites are polluted by arsenic, chromium, copper, lead, nickel and zinc.

To assess the level of contamination, the index of geo-accumulation (I_{geo}), (Muller, 1969; Krzysztof et al, 2003) was calculated for soil samples and mine wastes, to assess the presence and levels of contamination (Table 3a, 3b).

$$I_{geo} = \log_2 \left[\frac{C_m}{1.5 \times BV} \right]$$

C_m = concentration of a given element in the tested soil;

BV = concentration of the element in the Earth's crust (background value); the background values after Levinson (1974) after Lar et al. (2003).

1.5 = a constant accounting for fluctuations in the content of a given substance in the environment. The negative of geo-accumulation indexes for some elements indicates the absence of contamination.

The use of the index of geo-accumulation is based on seven descriptive classes for increasing I_{geo} values shown in Table 4.

Table 3a: Igeo values for some elements in the soil

Element Igeo	As	Co	Cr	Cu	Pb	Zn	Ni
S1	-0.24	1.04	0.84	1.20	0.90	-0.03	0.51
S2	2.17	1.38	0.83	1.52	1.51	0.04	0.58
S3	0.64	1.03	1.04	1.29	0.47	-0.18	0.69
S4	0.51	1.24	1.27	1.26	0.57	0.05	1.00
S5	-0.65	0.51	0.52	0.70	0.66	-0.63	-0.06
S6	0.20	1.05	0.95	1.07	0.49	-0.27	0.69
S7	0.97	1.08	0.87	1.10	0.51	-0.44	0.19
S8	0.71	1.17	1.60	1.20	0.40	-0.15	1.25
S9	1.46	1.21	0.97	1.32	1.03	0.39	0.46
S10	1.18	1.13	0.82	1.20	0.49	0.07	0.53
S11	1.67	1.31	1.58	1.45	1.30	0.19	0.48
S12	0.30	1.04	1.14	1.08	0.51	-0.25	0.61
S13	0.93	1.09	0.74	1.10	0.51	-0.40	0.30
S14	0.36	0.97	0.88	0.89	0.57	-0.30	0.21
S15	0.30	0.91	0.76	0.98	0.44	-0.36	0.35
SNC1	0.90	1.12	0.97	1.02	0.59	-0.36	0.31

Table 3b: Igeo values for some elements in the mine wastes

Element Igeo	As	Co	Cr	Cu	Pb	Zn	Ni
W1	1.95	0.36	-0.18	0.71	1.16	-0.15	-0.11
W2	0.27	1.41	1.06	1.73	0.19	0.45	0.96
W3	2.40	1.38	0.72	1.44	0.90	0.36	0.80
W4	1.29	0.50	0.27	1.07	-0.06	-0.33	-0.37
W5	3.25	1.40	0.97	2.55	2.80	1.29	1.00
W6	2.39	0.62	0.38	0.88	0.86	-0.10	0.16
W7	1.83	1.41	0.93	1.47	0.51	0.15	0.65
W8	1.80	1.12	0.12	1.25	0.24	-0.12	0.26
W9	2.14	1.28	1.61	2.23	2.73	1.30	1.13
W10	>3.65	1.21	0.30	2.22	2.95	0.55	0.90
W11	>3.65	1.43	0.51	2.34	2.85	1.08	-0.11

Table 4: Igeo classes with respect to soil quality

Igeo value	Igeo class	Designation of soil quality
> 5	6	Extremely contaminated
4-5	5	Strongly to extremely contaminated
3-4	4	Strongly contaminated
2-3	3	Moderately to strongly contaminated
1-2	2	Moderately contaminated
0-1	1	Uncontaminated to moderately contaminated
0	0	Uncontaminated

According to these classes, soils are uncontaminated to moderately contaminated (class 1) by arsenic, cobalt, chromium, copper, lead, zinc and nickel. They are moderately contaminated (class 2) by arsenic, cobalt, chromium, copper, lead and nickel. The Igeo class 3, i.e. moderately to strongly contaminated sites concerns only arsenic.

Concerning mine wastes, Igeo classes 1 and 2, i.e. respectively uncontaminated to moderately contaminated and moderately contaminated concern both element in table 4 (arsenic, cobalt, chromium, copper, lead, zinc and nickel). The highest degrees of contamination are caused

by arsenic, copper and lead (class 3: moderately to strongly contaminated sites) and by arsenic (class 4: strongly contaminated sites). So, in soils and mine wastes, the most harmful element is arsenic. Arsenic, copper and lead are the main constituents of sulfides (arsenopyrite: FeAsS, chalcopyrite: CuFeS, galena: PbS) encountered in the mineralized host rocks at Poura. This explains their high concentrations in mine wastes that resulted from the ore treatment or waste rocks.

According to Smedley et al (2007), the source of arsenic in Burkina Faso, is likely to be the oxidized sulfide minerals and secondary iron oxides in the mineralized zones. For these authors, high-As groundwater observed derive from zones of gold mineralization in Birimian (Lower Proterozoic) volcano-sedimentary rocks, the gold occurring in vein structures along with quartz and altered sulfide minerals (pyrite, chalcopyrite, arsenopyrite). This is consistent with the assumption mentioned above. Therefore, the high arsenic concentrations in soils and groundwater would be the host rocks of gold mineralization. At Poura, soil contamination in arsenic would come from mine wastes stockpiles stored for many years.

Indeed, in the problems of environmental pollution, the main parameters to consider are the source, intensity, extent and vulnerability. If the source (oxidation of mine waste or AMD), the intensity (Igeo and Igeo classes) and extent (contaminated sites) can be established, it is not the same the vulnerability without analyzes e.g. of plants, crops, blood, urine or hair.

So, concerning vulnerability, despite the lack of analysis of plants and crops, heavy metals released into the environment through the oxidation of mine wastes can be absorbed by plants. Indeed, several studies e.g. Álvarez et al (2003), Huang (2007), Zhang et al (2009), Lar et al (2013), Park and Choi (2013), Kalagbor and Diri (2014) have shown that plants can absorb heavy metals that will be eventually encountered in their fruits, leaves and tubers. In addition, heavy metals and potentially harmful element released by the oxidation of mine wastes can be transported in the Mouhoun River which is the main river in the region. The populations will be contaminated as a result in the consumption of fishes that have ingested these different toxic elements.

CONCLUSIONS

This study shows that mine wastes stockpiles at Poura, are oxidized in some places, due to their exposure during several years to water and atmospheric agents. This oxidation is the source of acidic pH of surface water or acidic effluents known as acid mine drainage (AMD). This acid mine drainage results in the solubilization of potentially harmful elements (arsenic, cobalt, chromium, copper, lead, zinc and nickel) that are subsequently released into the environment.

The index of geo-accumulation (Igeo) and the descriptive classes for increasing Igeo values indicate that arsenic, copper and lead are the most harmful elements. The soil is moderately contaminated (class 2) by arsenic, cobalt, chromium, copper, lead and nickel, then moderately to strongly contaminated (class 3) by arsenic. For mine wastes, moderately contaminated sites (class 2) are due to arsenic, cobalt, chromium, copper, lead, zinc and nickel; moderately to strongly contaminated (class 3) by arsenic copper and lead; strongly contaminated (class 4) by arsenic which appears to be the most polluting element.

The source of these elements that cause the phenomenon of contamination would be sulfides and other metallic minerals which constitute the host rocks of the mineralization and are encountered in mine wastes.

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