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The environmental impact of sulphide mines measured with organogenic sampling media

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Abstract—The environmental impact of an active and an abandoned mine was studied using several different sampling media. The emphasis was on organic and organic-rich materials such as humus, moss and organic stream sediment. The chemical processes in the waste were studied in samples obtained by drilling through the waste into the ground beneath.

Both total and bioavailable element concentrations were measured. The abundances of more than 30 elements were determined, but since the distribution patterns were similar, discussion in this paper is focused on As, Cd, Cu, Fe, S and Zn.

The high capacity of humus, moss and organic sediments for binding heavy metals and S made them excellent media for studying the distribution of elements in the vicinity of the mining area. The airborne contamination from the active mine was detectable at distances of 2 to 3 km, but from the abandoned mines only about 100 m. The airborne distribution patterns recorded for the various elements were approximately the same for all sampling media and analytical methods. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Fine-grained tailings generated during the enrichment of sulphide ores are generally directed to tailings ponds or dams in the vicinity of the processing plant. If the waste becomes oxidized, the seepage from the tailings areas may lead to contamination of the surrounding area with heavy metals and S (e.g. Boorman and Watson, 1976; Brandt *et al.*, 1987; Södermark and Lundgren, 1988). Windborne dust formed by the drying of the surface of the tailings dump is another source of environmental problems (e.g. Salomons and Förstner, 1988). This study, which is a part of a much larger investigation project (Sipilä, 1994), addresses the environmental problems associated with tailings dumps at two sulphide mines in Finland. One had already been mined out, the Aijala deposit having closed down in 1974, and the tailings had not been prevented from oxidizing, but the other one, the Pyhäsalmi mine, where mining is still continuing, oxidation has been prevented by keeping the tailings dam covered with water.

A variety of leaching techniques were used to emulate differing environmental conditions, with strong acids being used to determine total abundances of potentially harmful elements, and weaker solutions to determine compounds that are relatively soluble and bioavailable.

The aim of this study was to ascertain the extent to which the tailings areas impact on the environment. Special attention was paid to the use of organic and organic-rich natural materials as sampling media.

METHODS

Description of target areas

Aijala The Aijala Cu–Zn–Pb deposit is located within the leptite zone of southwestern Finland. Mining activity commenced in 1949 and ceased in 1974. Tailings were dammed in a natural topographic depression between areas of higher ground and cover an area of 14 ha. Nearly 2 Mt of concentrate tailings were dumped, containing on average 0.12% Cu, 0.50% Zn, 0.11% Pb and 0.69 ppm Au. The upper parts of the tailings have become oxidized.

The tailings at Aijala contain sulphides, silicates and carbonates. Pyrrhotite and carbonate have been leached from the oxidized zone, but are still found below the water table.

Pyhäsalmi The Pyhäsalmi Cu–Zn–S deposit is situated within the Ladoga–Bothnia sulphide ore zone. Mining operations began in 1962 and reserves are expected to be depleted around the year 2000. About 1.1 Mt of ore is mined annually. The tailings dump is located between the concentrator and nearby Lake Pyhäjärvi, and is entirely above the water table. The dump presently covers an area of 150 ha and contains about 10 Mt of tailings. Waste has been dumped into two sites, the A pond, which has been used since the inception of mining, and the D pond which was filled with the tailings between 1977 and 1984. The A pond is estimated to contain 7.8 Mt of tailings with average concentrations of 0.07% Cu, 0.31% Zn and 13.2% S, while the D pond contains 2.2 Mt of S tailings, with contents of 0.08% Cu, 0.20% Zn and 27.4% S.

Sampling

Field work was carried out during the summer of 1992. Organic material was collected from stream and lake sediments in order to evaluate the distribution and extent of contamination spread by surface waters. The impact of dust derived from the tailings dumps was assessed by sampling feather moss (*Hylocomium splendens*) and humus. Moss and humus were sampled from the same sites along profiles leading away from the dumps.

Samples of the Pyhäsalmi tailings, and of the overburden beneath and surrounding the tailings dumps, were obtained by drilling. The only material available from the Aijala dump consisted of tailings.

Analytical methods

Samples were dried at temperatures below 40°C, to preclude the evaporation of any mercury that might be present. For the total abundances, tailings samples were leached with a hot 7 M nitric acid (HNO_3) solution and soil samples with a hot aqua regia solution. The less soluble components of the sediment, humus and moss samples were dissolved in a microwave-assisted leaching with 7 M HNO_3 solution.

Readily soluble elements in sediment, humus and moss samples, as well as in soil samples, were leached with a 1 M ammonium acetate solution at pH 4.5 The waste material was leached with a simulated rainwater solution consisting of a mixture of H_2SO_4 and HNO_3 and having a pH of 4.5.

Some 30 elements were determined in each sample, by ICP-AES or ICP-MS. The element abundances of organic samples are expressed as in dry matter. Only the results from As, Cd, Cu, Fe, S and Zn are discussed here.

RESULTS

The high capacity of the organic material of moss, humus and sediment to bind S and heavy metals was well demonstrated in this study. The element concentrations of mosses describe the mining activities during the last 3 to 4 years. The highest concentrations in the area of active Pyhäsalmi mine were almost tenfold (maximum values of Cd 1.2 ppm and S 6360 ppm) those in a clean background area (<0.50 and 1300 ppm, respectively) (Table 1 and Fig. 1A). In the old abandoned Aijala mining area even the highest values (Cd 1.0 ppm and S 2550 ppm) were lower than the majority of values at Pyhäsalmi, and a very noticeable difference was that the impact of the dump could be detected only in the nearest samples, which were taken less than a 100 m from the edge of the dump (Fig. 2A).

The older history of the mining is registered in the humus (Table 2). At Aijala the surface of the NW-corner of the dump was covered by till and gravel about 20 years ago and is now further covered by vegetation. Metal and S concentrations of humus were high on all sides of the dump, but moss samples to the NW of the dump exhibited typical background values. The distribution pattern of Cd is presented as an example in Fig. 2A and B. Evidently no dust from the dump had been deposited there during the last 3 to 4 years — the life time of the mosses. Correspondingly, in the Pyhäsalmi area, the collapse of the tailings pond dam some years ago in the SW-corner of the dump caused very high metal and S concentrations in humus — the only remaining sign of that accident (Fig. 1A). Because of the high metal and S concentrations and low pH of the soil, this area does not even support mosses (Fig. 1B).

As a rule the S concentrations of organic sediments and humus are high wherever the influence of mining is prevailing. The median S value of stream sediment (Table 3) was 2475 ppm at Pyhäsalmi and 4320 ppm at Aijala, and that of humus (Table 2) 3750 ppm and 1880 ppm, respectively. Typical background values reported in some local and regional scale studies in Finland have been less than 1000 ppm (Äyräs and Niskavaara, 1992; Kohonen and Salminen, 1993; Lahermo *et al.*, in preparation).

In Finland, the tailings ponds have usually been established in lake or peat bog basins. An organic-rich layer of gyttja or peat regularly occurs at the bottom of these basins. This was the case in the target mines of our study, too. This organic-rich layer has played an essential role in preventing the seepage of metal and S ions through the bottom of the tailings pond into the ground. As can be seen in Fig. 3A and B, in all samples studied, the metal and S concentrations in the minerogenic overburden underlying the dump exhib-

Table 1. Median, minimum and maximum values of element abundances in mosses

	As	Cd	Cu	Fe	S	Zn	*N*
Aijala							
median	<3.0	0.63	5.80	670	1210	61.40	20
min.	<3.0	0.31	3.25	382	882	35.00	
max.	15.80	1.00	17.10	5230	2550	165	
Pyhäsalmi							
median	<3.0	<0.50	92.45	836	1770	88.00	14
min.	<3.0	<0.50	31.50	390	1240	58.40	
max.	<3.0	1.20	527	5930	6360	298	

Total abundances (ppm); *N* = number of samples.

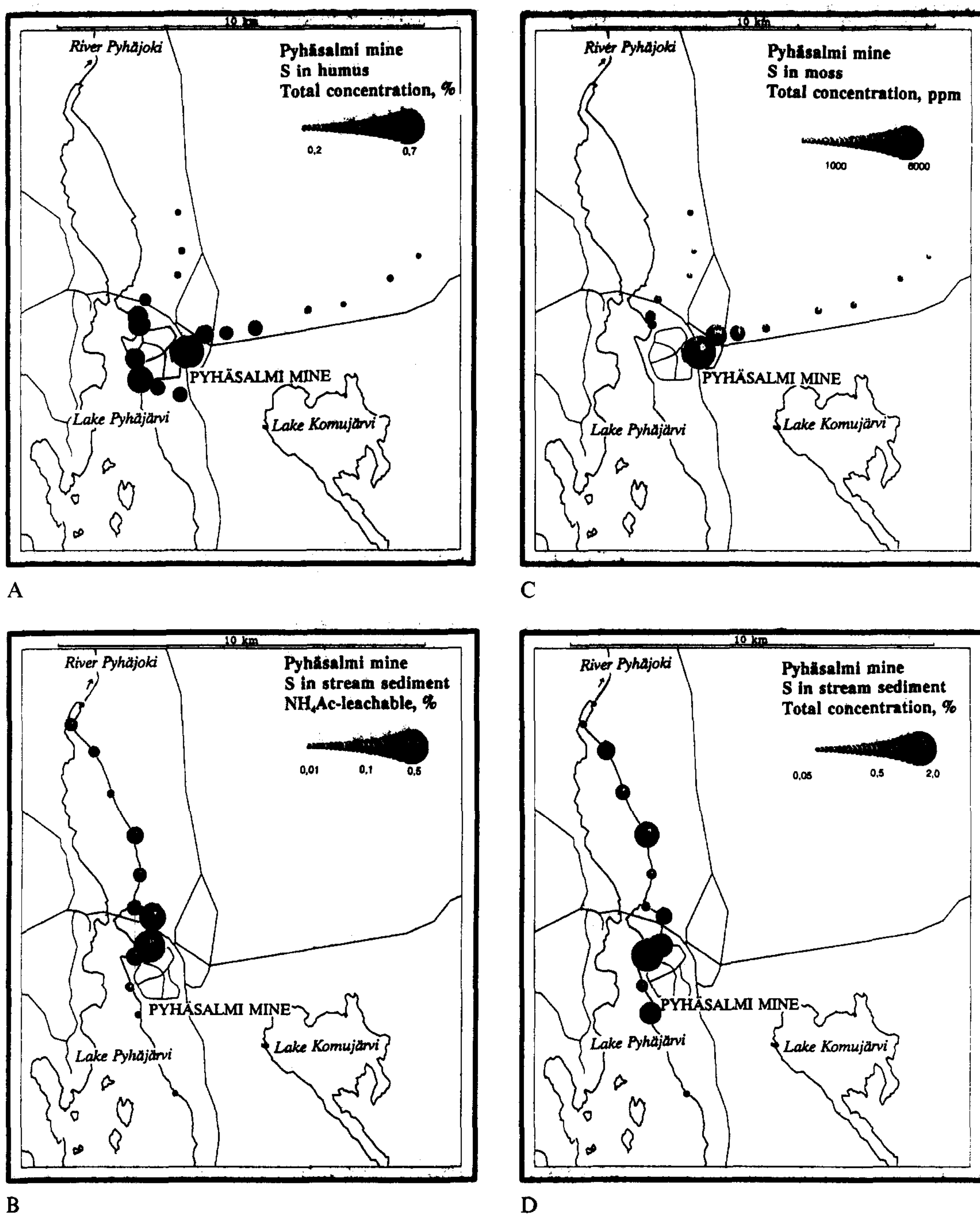
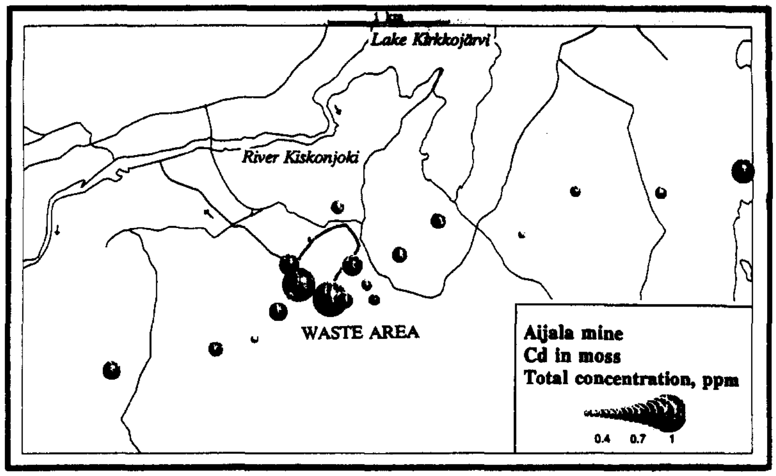


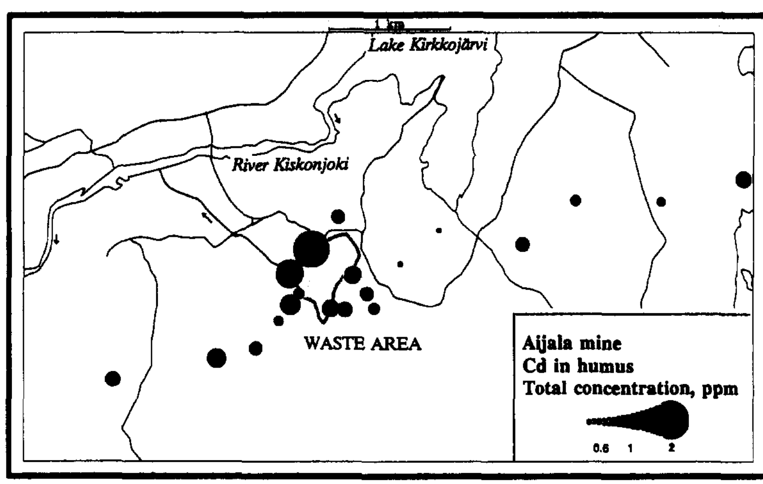
Fig. 1. The distribution of sulphur in the vicinity of Pyhäsalmi mine. (A) Total concentration (%) in humus, dry matter; (B) Total concentration (ppm) in feather moss, dry matter; (C) Bioavailable (leached with ammonium acetate) concentration (%) in organic stream sediment, dry matter); (D) Total concentration in organic stream sediment (%), dry matter.

ited only typical background values if there was a peat or other organic-rich layer between the waste and the ground. The metal concentration of the organic layer was high and metals there were in easily leachable form.

The bioavailable metal and S concentrations (Tables 1–3) were low in all materials studied, and the proportion of easily leachable amount to total abundance (Table 4) was usually less than 1%. The only exception was Cd. Its total abundance in the oxidized waste of Aijala mine was 2.7 ppm (median value) and the bioavailable abundance was more than 40%; while at Pyhäsalmi the corresponding values were 8.5 ppm (median value) and 5% (Table 1). The distribution patterns of easily leachable and total concentrations did not differ appreciably (Fig. 1C



A



B

Fig. 2. The distribution of Cd in the vicinity of Aijala mine. (A) Total concentration (ppm) in feather moss, dry matter; (B) Total concentration (ppm) in humus, dry matter.

and D). In this study, Cd was the only element, that was leached in harmful amounts and in harmful form from the waste areas of the mines.

DISCUSSION

There are two main routes by which heavy metals and S are distributed from a mining area: by air as dust to the surrounding area and by seepage waters to streams and lakes. Although the distribution patterns were different in airborne and waterborne mechanisms, the distribution patterns of the various elements were more or less similar in the same sampling medium and did not differ much even in different sampling media, when the transport mechanism was the same.

The best natural materials for registering the airborne distribution of heavy metals are mosses and humus. Mosses obtain nutrients directly from air and thereby incorporate airborne impurities. The part of moss sampled represents the last 3 to 4 years growth. Moss samples have recently been used to measure the airborne heavy metal pollution in urban areas (Mäkinen *et al.*, 1991) and in regional mapping in the Nordic countries (Rühling *et al.*, 1992). These materials together with organic sediment can be recommended in investigations of the distribution of heavy metals and S from a mining area.

The airborne distribution of heavy metals from the active sulphide mine was detected approximately 2 km away, but from the abandoned mine not even 100 m. The lower concentrations can be attributed to leaching of the oxidized surface layer of the waste during the past 20 years, which has removed metals and S from the dusting layer. In general, in spite of dusting from the parts where the dump is not covered by water or vegetation, the amount of harmful elements in the dust is never so great in an abandonded mine like Aijala as in an active mine.

Table 2. Median, minimum and maximum values of element abundances (ppm) in humus

	As	Cd	Cu	Fe	S	Zn	*N*
Aijala*							
median	5.40	1.05	18.75	4020	1880	110.50	20
min.	<3.0	0.47	8.18	2070	1230	49.60	
max.	81.80	1.96	68.00	26,900	3000	230	
Aijala†							
median	1.17	0.28	0.15	18.40	122	21.85	20
min.	0.66	0.17	0.05	4.13	94.80	11.70	
max.	3.26	0.75	2.69	1110	244	66.10	
Pyhäsalmi*							
median	<3.0	0.97	248	7680	3750	138	18
min.	<3.0	<0.3	26.60	1170	1830	24.30	
max.	23.70	4.30	625	59,200	6640	698	
Pyhäsalmi†							
median	0.73	0.29	3.22	30.95	177	28.25	18
min.	0.50	0.03	0.06	2.03	91.00	5.38	
max.	1.61	1.68	35.50	4970	1920	207	

*Total abundances (determined by ICP-AES). †Easily leachable abundances (determined by ICP-MS).

Humus, unlike mosses, has been collecting airborne material ever since its formation, which means that practically the whole history since the latest glaciation may have been registered. Migration of ions into and out of humus is continually taking place, however, according to the chemical equilibria, prevailing pH–Eh-conditions and the chemical compounds participating in the reactions. The capacity of humus to bind heavy metal ions is nevertheless many times that of other natural materials. Although this is mainly due to the high ion exchange capacity of organic material, there are other mechanisms to catch metal ions, too. This special feature of organic materials like humus and peat has even successfully been exploited in purifying the seepage waters from tailings ponds (Lapakko and Eger, 1988) and should be seriously taken into account in planning new dumps.

Stream and lake sediments were contaminated up to a distance of 5 km from the active mine, where waste was neutralized and the dump was water covered, but

Table 3. Median, minimum and maximum values of element abundances (ppm) in organic stream sediments

	As	Cd	Cu	Fe	S	Zn	*N*
Aijala*							
median	16.6	1.42	77.10	29,800	4320	302	14
min.	<3.0	<0.3	7.25	9580	458	44.40	
max.	333	29.90	1770	177,000	28,400	4890	
Aijala†							
median	1.21	0.73	2.37	2000	540	61.55	14
min.	0.54	0.06	0.36	50.70	34.20	3.99	
max.	2.31	5.41	195	2000	4330	1100	
Pyhäsalmi*							
median	5.53	0.72	67.75	26,850	2475	128	20
min.	<3.0	<0.3	6.20	16,500	291	27.60	
max.	49.00	34.00	809	75,800	15,500	1280	
Pyhäsalmi†							
median	0.80	0.37	0.85	251	358.50	25.95	20
min.	0.42	0.04	0.09	95.90	31.40	2.61	
max.	4.12	19.60	25.20	1390	4230	385	

*Total abundances. †Easily leachable abundances.

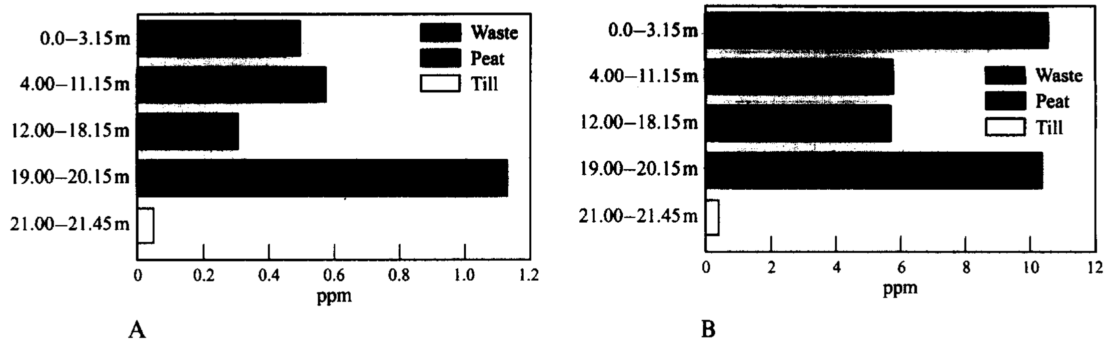


Fig. 3. Cadmium concentration (ppm) in a profile through the waste and underlying peat and till in the tailings area of the Pyhäsalmi Cu–Zn-mine. (A) Rainwater leachable abundances; (B) Total abundances. Depth of the analysed sample on the vertical axis.

Table 4. Total and rainwater leachable concentrations (median values) of selected elements in the surface layer of the waste at an abandoned mine (Aijala) and an active mine (Pyhäsalmi). Number of samples at Aijala 8 and at Pyhäsalmi 20

	Total (ppm)	Rainwater leachable (ppm)	Proportion of rainwater leachable from total (%)
Arsenic			
Aijala	150	<0.5	<0.3
Pyhäsalmi	100	<0.5	<0.5
Cadmium			
Aijala	2.7	1.1	40.7
Pyhäsalmi	8.5	0.4	4.7
Zinc			
Aijala	3000	80	2.7
Pyhäsalmi	2200	35	1.6
Copper			
Aijala	390	1.0	0.3
Pyhäsalmi	1000	0.1	0.01
Sulphur			
Aijala	47,000	3200	0.7
Pyhäsalmi	152,000	2900	1.9

contamination was detected 20 km downstream in the case of the abandoned mine with oxidizing waste material in the dump.

The high concentrations of S and heavy metals in the gyttja and peat beneath the tailings show that these materials act as a trap, preventing the seepage of heavy metals to the overburden beneath the waste.

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