



Oxygen penetration and subsequent reactions in flooded sulphidic mine tailings: a study at Stekenjokk, northern Sweden

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Abstract

A study of O₂ penetration and pore water geochemistry of the flooded tailings at Stekenjokk has been performed. The results show that there is a diffusion of elements from the tailings pore water to the overlying water. The presence of elements such as Ca, Mg, S, Si, Ba and Sr are likely the result of diffusion of older process water trapped in the tailings. Oxygen concentrations in the tailings measured with microelectrodes show that there is O₂ available down to 16 to 17 mm depth in the tailings. Pore water analyses show that there are subsurface maxima for the elements Cu, Zn, Ni, Co and Cd at depths of 0.25 to 2.75 cm. The highest concentrations of almost all elements were found where previously oxidised material was deposited before the flooding. Lower pH is measured in the uppermost part of the tailings compared with the pond water and the tailings pore water at depth. Oxidation of sulphides in the uppermost part of the tailings is probably occurring. A decrease in oxidation rate can be expected in the future due to deposition of organic material at the tailings surface. Flooding seems to be an efficient remediation method at Stekenjokk. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Various methods have been developed or suggested to prevent the formation of acid drainage from sulphide mining waste. One method is to limit the supply of O₂ by covering the waste with water. Water covers have been shown to strongly inhibit the oxidation rates of sulphide-bearing mining wastes. Recent studies in Canada, where sulphide-rich Zn-, Cu- and Pb-bearing tailings have been deposited in natural lakes, have given encouraging results (Fraser and Robertson, 1994; Pedersen et al., 1994, 1997). In these studies low concentrations of Cu, Zn, Cd, Pb and other metals were found in the sediment pore waters. There seemed to be no or only minor diffusion of dissolved metals from

the sediments and pore water to the water column in the lakes.

Flooding of tailings is comparable to the situation with deposition in natural lakes if the waste has not been exposed to oxidising conditions. Flooding may, therefore, have the potential to be a cost effective remediation method. The water cover acts as a barrier against O₂ supply, but it does not totally stop the diffusion of O₂ to the tailings. Laboratory studies indicate that sulphide oxidation may occur at a non-negligible rate in water-covered waste (Payant et al., 1995; Aubé et al., 1995). Before the applicability of flooding as a remediation method is completely understood, there is an urgent need to research how flooding affects weathering and transport processes in waste.

The sulphide-rich mill tailings of the Stekenjokk Cu–Zn mine in northern Sweden were flooded in 1991 (Broman and Göransson, 1994), and offer a good opportunity for field studies of the efficacy of this remediation method. During 1995 such a study was

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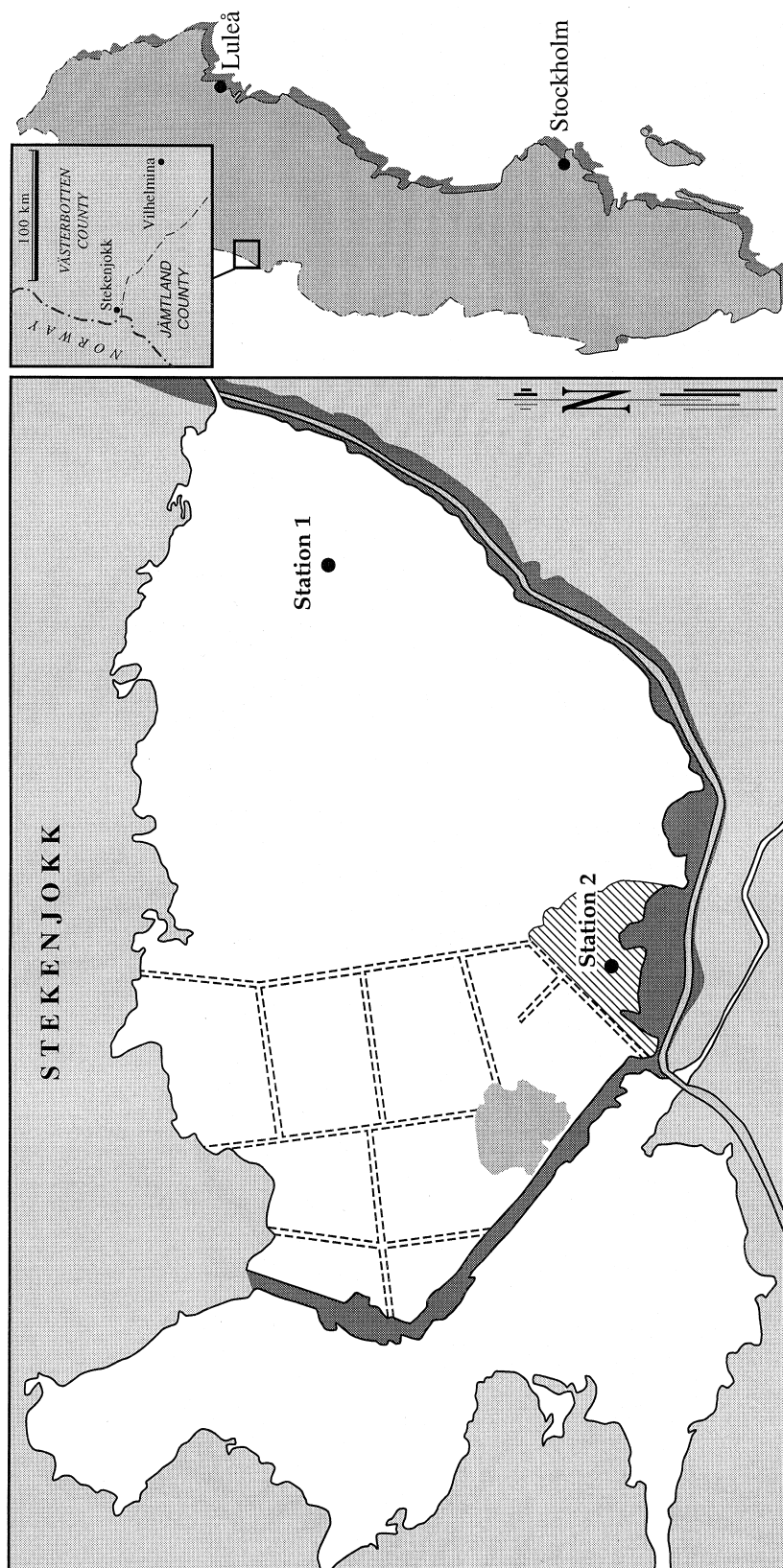


Fig. 1. Map showing the location of the Stekenjokk mine and the flooded tailings pond with the sampling locations marked.

performed (Ljungberg et al., 1997), and the results of that study indicated that the dissolved concentrations of especially Zn (*c.* 139 µg/l) and Cd (*c.* 0.69 µg/l) in the pond were elevated compared with the natural background (*c.* 13 µg/l Zn and 0.06 µg/l Cd). There were also indications that sulphide oxidation was occurring in the uppermost part of the tailings. The study also showed that the area where previously oxidised tailings were deposited contributed Zn to the pond water at a higher rate than areas of unoxidised tailings. To study whether sulphide oxidation is currently occurring, high quality samples of pore water and profiles of the tailings were obtained in September 1997. The results are presented in this paper.

2. Site-description

Stekenjokk is a stratabound volcanogenic Zn–Cu deposit of Caledonian age (Zachrisson, 1971), situated in northern Sweden (Fig. 1), close to the Norwegian border. The average grade was 3.2% Zn, 1.4% Cu, 0.3% Pb and 40 ppm Ag (Juve, 1974). Major sulphides present were pyrite, sphalerite and chalcopyrite. Galena, pyrrhotite, covellite and minor amounts of arsenopyrite also occurred. The gangue minerals were quartz, feldspars, sericite, chlorite and carbonates. Mining operations by Boliden Mineral AB lasted from 1976 to 1988, and 8.08 million tonnes were mined mainly by underground cut and fill operations. A minor volume of ore was mined from an open pit. Mining left waste rock dumps and some 4.4×10^6 tonnes of tailings. The tailings consists of about 35% sulphides; mainly pyrite, but chalcopyrite, sphalerite, pyrrhotite, and galena also occur. The high content of pyrite makes the tailings a potential source of acid drainage. The heavy metal concentrations of the tailings solids are high, with for example, 2266 ppm Cu, 1458 ppm Pb, 6829 ppm Zn together with 1139 ppm As (Table 1). The CaCO_3 content in the tailings is *c.* 5 to 15%. The materials deposited in the tailings and clarification pond consisted of 71% silt- and clay-sized grains (<60 µm grain diameter), and 29% of the material had grain diameters between 60 µm and 2 mm (Boliden Mineral AB, 1989).

A decommissioning programme based on flooding was completed in 1991 (for a detailed description, see Broman and Göransson, 1994). Flooding was achieved by raising the water level in the tailings and clarification pond by raising the existing dykes. Some parts of the tailings were redeposited to lower the surface of the upstream tailings area. A small area (*c.* 5%) of the tailings deposit consisted of material which was partially oxidised and weathered before the flooding, but the major part of the tailings was unoxidised. The already oxidised material is richer in sulphides and is

Table 1

Average composition of the tailings at Stekenjokk. 33 analyses from Ljungberg et al. (1997) are included

Element	Stekenjokk unoxidised tailings (53 samples)
	[weight% ± s.d]
SiO ₂	35.5 ± 6.4
Al ₂ O ₃	5.89 ± 2.27
CaO	5.73 ± 2.38
Fe ₂ O ₃	28.0 ± 4.6
K ₂ O	0.79 ± 0.26
MgO	4.60 ± 1.91
MnO	0.11 ± 0.09
Na ₂ O	0.42 ± 0.27
P ₂ O ₅	0.22 ± 0.04
TiO ₂	0.17 ± 0.08
LOI	17.0 ± 4.6
	[ppm ± s.d]
As	1139 ± 351
Ba	252 ± 110
Be	1.68 ± 0.40
Cd	31.9 ± 15.7
Co	61.4 ± 19.5
Cr	31.1 ± 16.7
Cu	2266 ± 806
Mo	48.6 ± 11.7
Ni	24.3 ± 9.7
Pb	1458 ± 389
S	177757 ± 55907
Sc	6.01 ± 3.36
Sr	81.9 ± 32.3
V	156 ± 30
Y	14.0 ± 4.09
Zn	6829 ± 3001
Zr	51.1 ± 20.6

more coarse grained than the normal tailings. A break-water system was built to prevent resuspension from the tailings surface. The pond has an area of 1.1 km² and a water volume of *c.* 2 Mm³. Water depth varies between 0.6 to 9 m, with an average of *c.* 2 m.

Stekenjokk is situated in the Caledonian mountains at an altitude of *c.* 800 m above sea level. Annual mean temperature is *c.* 0°C, and the annual precipitation *c.* 1100 mm (Boliden Mineral AB, 1989). The area is open without forest because it is situated above the tree limit. Strong winds are very common. The pond is covered with ice from October to June. Surface run off waters enter the dam in two minor streams on the western side, and the outlet is located on the north-eastern side. The annual discharged water volume in the outlet is *c.* 2 Mm³, resulting in a renewal time of approximately one year for the water mass in the pond.

During 1988, the last year of production, 1.8 Mm³ of process water was used in the concentrator.

Approximately 75.2 tonne CuSO_4 , 154.6 tonne SO_2 and 455 tonne Ca(OH)_2 was added to the water. The monitoring program of the outlet water showed average concentrations of SO_4^{2-} , Zn, Pb and Cu during 1988 of 293, 0.180, 0.015 and 0.025 mg/l, respectively. From 1978 to 1987 the annual average SO_4^{2-} concentration ranged between 126 and 444 mg/l, and Zn ranged from 0.127 to 0.347 mg/l. The pH varied between 7.0 and 8.4.

3. Methodology

3.1. Sample collection

Two cores were sampled from the tailings at different locations (Stations 1 and 2 in Fig. 1) using a modified Kajak gravity corer with a Plexiglass[®] tube (\varnothing 85 mm). The core from Station 1 sampled unoxidised tailings and the core from Station 2 sampled partially oxidised tailings. In order to minimise the disturbance of the tailings-water interface, a diver slowly pressed the corer into the tailings and sealed the Plexiglass[®] tube. Only cores with an undisturbed surface were accepted. The cores were divided into 0.5 cm subsamples for the first 5 cm, and into 1 cm subsamples thereafter in an Ar-atmosphere immediately after collection. The tailings samples were stored in acid-washed polyethylene plastic bags that in turn were stored in Ar-filled 2 litre plastic bottles. The core sampled at Station 1 had a length of 26 cm and the core at Station 2 a length of 12 cm.

At both locations pH, temperature, depth and dissolved O_2 of the pond water were measured in situ using a Hydrolab[®] Surveyor II water quality probe. Bottom pond water samples were collected 2 cm above the tailings surface using an acid washed syringe. The bottom water samples were stored in acid washed bottles and filtered through 0.22 μm Millipore[®] filters.

Pore water was extracted within a few hours after collection of the cores using a glove-box filled with Ar. The pore water was extracted by vacuum filtering using a portable Masterflex[®] vacuum pump and an acid washed filterholder. The pore water was filtered through 0.22 μm Masterflex[®] filters and was collected into double acid washed test tubes. Prior to use the test tubes were filled with 0.14 M HNO_3 . From 2 to 10 ml of pore water was extracted from each sample.

In order to avoid contamination all equipment used was acid-washed in 5% HNO_3 . Blanks were taken before and after pore water extraction. A blank was also taken from the Milli-Q[®] water used. The pH of wet tailings was measured during pore water extraction using a Metrohm[®] pH-electrode calibrated with pH 4 and pH 7 Titrisol[®] buffers.

3.2. Oxygen measurements using microelectrodes

Microelectrodes have successfully been used in many studies to describe O_2 profiles in natural sediments (e.g., Gundersen and Jørgensen, 1990, 1991; Rasmussen and Jørgensen, 1992). Microelectrodes manufactured by the Institute of Biological Sciences, University of Aarhus, Denmark were used in this study. The microelectrodes have a sensing-tip diameter of $< 10 \mu\text{m}$ and a 90% response of 1 s. The microelectrodes were mounted in a micromanipulator with a resolution of 10 μm .

Checks done show that the measurements made with the Hydrolab[®] II water quality probe should correlate with the measurements done with the microelectrodes. The checks were conducted using both the Hydrolab[®] II water quality probe and the microelectrodes simultaneously. Water with a known temperature was used and the barometric pressure was measured during the tests. The microelectrodes, however, are very sensitive to the calibration temperature and ideally the temperature should be the same as in the media where the measurements are made.

Linear calibration was done on pond water at full O_2 saturation and pond water under anoxic conditions. Full O_2 saturation was achieved by bubbling O_2 through the water and anoxic conditions were achieved by bubbling Ar. The temperature increased by 2 to 4°C during the calibration compared with the in situ water temperature. However, the tailings temperature may well be higher compared with the temperature of the overlying pond water. Unfortunately, this means that there may be errors in the microelectrode measurements of dissolved O_2 concentration, though the relative trends should be correct.

3.3. Chemical analysis

Due to the small amount of pore water, Fe, Al, As, Ba, Cd, Co, Cr, Cu, Mn, Ni, Pb and Zn were analysed using ICP-SMS (high resolution ICP-MS) and alkalinity was not measured. Calcium, K, Mg, Na, S, Si and Sr were analysed by ICP-AES. All samples were analysed at SGAB (Svensk Grundämnesanalys AB), Luleå, Sweden.

4. Results

4.1. Water column measurements

The cores were sampled at two different locations with different water depths. The water depth at Station 1 was *c.* 9 m and at Station 2 *c.* 2 m, respectively. At each location temperature, pH, conductivity and the dissolved O_2 concentration of the water column were

measured. The profiles of temperature, pH, conductivity and dissolved O₂ of the pond water at both stations show that it was well-mixed at the time the samples were collected (Fig. 2). This agrees with the results of Ljungberg et al. (1997). All parameters are fairly similar at both stations. The temperature ranges from 3.96 to 4.16°C (Fig. 2a,e) with slightly lower temperatures at Station 2. The pH varies from 7.57 to 7.78 (Fig. 2b,f), indicating the well buffered nature of the tailings. The conductivity varies from 106.5 to 108.4 µS/cm (Fig. 2c,g) with slightly higher values at Station 2. The concentration of dissolved O₂ ranges from 11.33 to 11.53 mg O₂/l with higher O₂ concentrations at Station 2 (Fig. 2d,h). These higher concentrations can probably be explained by the lower temperature at this location.

4.2. Studies of the tailings-water interface

Studies of the tailings-water interface were made in situ by the diver during core collection and by inspecting the collected cores. The studies showed that there is a coherent organic layer approximately 0.5 cm thick covering the tailings. Although mostly consisting of organic material this layer also contains significant amounts of tailings. A mean sedimentation rate of 0.8 mm/a may be calculated since the flooding was completed in 1991, based on the average thickness of the organic layer (approximately 0.5 cm). Red alternating layers, a few mm thick, probably rich in Fe- and Mn-oxyhydroxides, were visible below the organic layer and above the dark-grey tailings in the core sampled at Station 1. On top of the core sampled at Station 2 small red nodules were visible.

The grain size of all tailings minerals was larger at Station 2 compared with Station 1. This may be due to waves that flush away the smaller particles which settle in deeper parts of the pond or a relict of spigoting locations during tailings discharge.

4.3. Microelectrode measurements

Two O₂ profiles were measured with the microelectrodes in each of the cores after collection. The profiles in each core were located with distances of around 2 to 3 cm from each other. The values of O₂ concentrations determined with the microelectrodes were somewhat higher in the upper layers of the tailings compared with measurements with the water quality probe in the water column of the pond. This is probably due to the difference between the temperature in which the microelectrodes were calibrated and the temperature of the tailings. However, even if the temperatures were the same, it is probable that the general trend of the profiles would be the same.

The two profiles from the core taken at Station 1 (Fig. 3a,b) show that there is O₂ available down to depths of 11 to 17 mm. In the core sampled at Station 2 the oxygen penetrates to depths of 14 to 17 mm (Fig. 3c,d). The profiles show that pore fluids at the tailings-water interface are saturated with respect to dissolved O₂ and that the real O₂ consumption occurs within the tailings itself, below the organic layer in all cases.

4.4. Pore water blanks

As mentioned earlier, blanks were taken before and after pore water extraction, and also on the Milli-Q[®] water used. The Milli-Q[®] blank of the water used shows only traces of Al (106 ng/l) and Ni (54 ng/l), and levels are below detection for the other elements (<5 to 2000 ng/l). The blanks before pore water extraction show only traces of Fe (150 to 330 ng/l), Al (212 to 268 ng/l), As (61 ng/l), Cr (8 ng/l), Cu (66 to 173 ng/l), Ni (66 ng/l) and Zn (154 to 195 ng/l). The concentrations in the blanks after pore water extraction were slightly higher for Fe (360 to 470 ng/l), Al (392 to 658 ng/l), As (63 to 64 ng/l), Ba (37 ng/l), Cr (5 to 11 ng/l), Cu (183 to 326 ng/l), Mn (8 to 12 ng/l), Ni (172 ng/l) and Zn (174 to 267 ng/l). It can be concluded, however, that almost no contamination of the samples occurred during the extraction process.

4.5. Pore water in the tailings

The concentration of Cd, Co, Mn, Ni, Pb and Zn at Station 1 increases to maximum values a few centimetres below the tailings-water interface and then generally decreases (Fig. 4a-b,d-g). The subsurface concentration peaks are clearly visible at depths 0.5 to 2 cm for Cd, Co, Ni and Zn. At Station 1 the concentrations of metals are: *c.* 6.6 µg/l Cd at 1.25 cm, *c.* 2.1 µg/l Co at 1.75 cm, *c.* 6.8 µg/l Ni at 1.75 cm, and *c.* 0.7 mg/l Zn at 0.75 cm. Copper also has a maximum subsurface concentration of *c.* 8.7 µg/l at 0.75 cm (Fig. 4c). However, the Cu concentrations vary more throughout the profile than the other elements. The peaks for Pb and Mn are situated somewhat deeper at a depth of 2.75 cm (*c.* 30 µg/l Pb and 0.6 mg/l Mn). The maximum concentration of total S (approximately 100 mg/l) also occurs at this depth (Fig. 5c).

At Station 2, Cd, Co, Cu and Zn have maximum concentrations between a depth of 0 and 2.5 cm (Fig. 4a-c,g). The maximum concentration of metals are: *c.* 7.9 µg/l Cd at 1.25 cm, *c.* 1.1 µg/l Co at 2.25 cm, *c.* 17.6 µg/l Cu at 0.25 cm and *c.* 1 mg/l Zn at 0.25 cm. Above and below these depths the concentrations are much lower and decrease. Manganese, Ni and Pb have peaks at *c.* 2.25 cm with concentrations of 4.3 µg/l Ni, 6.7 µg/l Pb and 130 µg/l Mn,

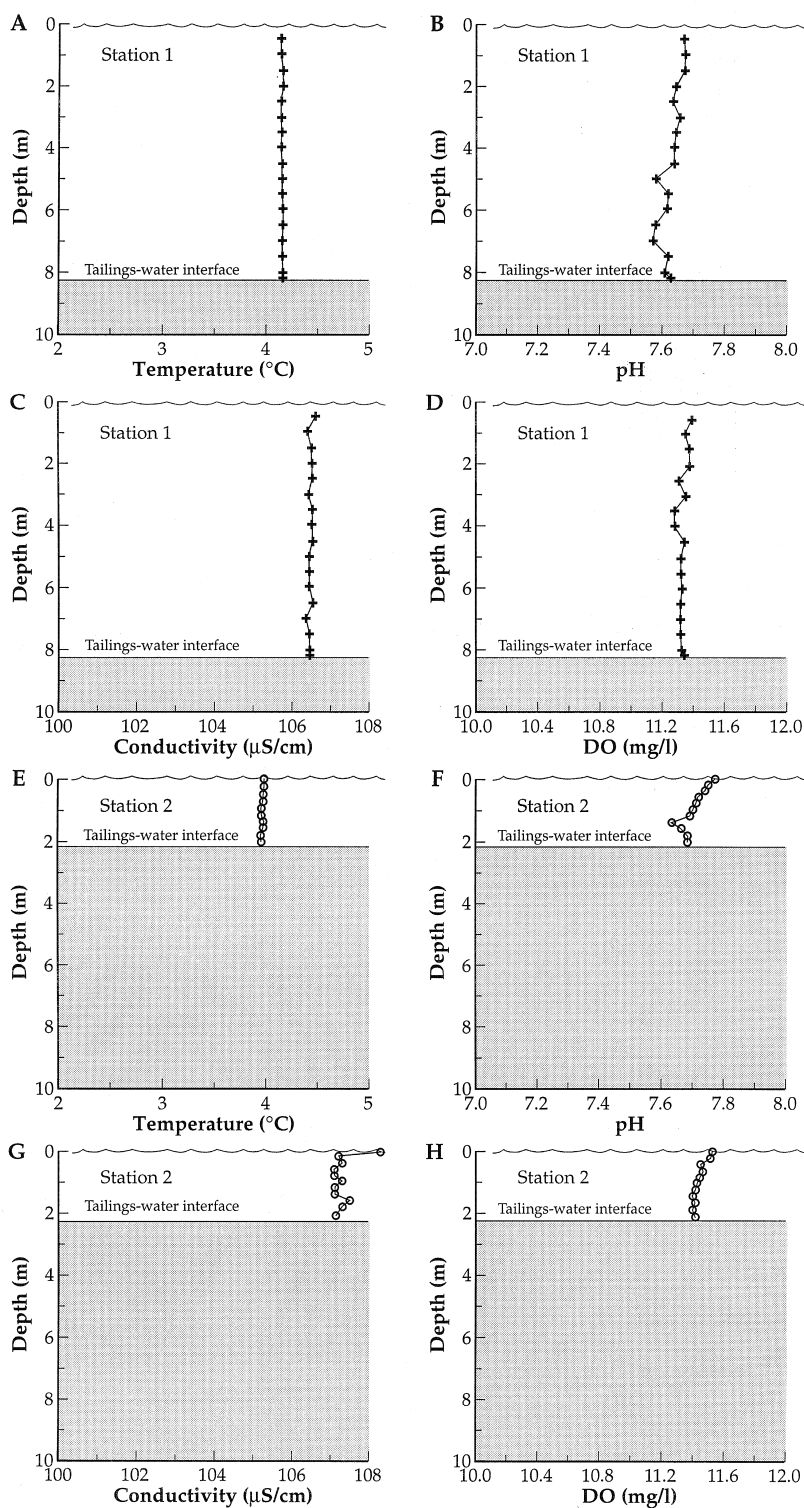


Fig. 2. Temperature (a, e), pH (b, f), conductivity (c, g) and dissolved oxygen (d, h) in the pond water from the water surface down to the tailings surface at Stations 1 and 2. Depth scale in metres.

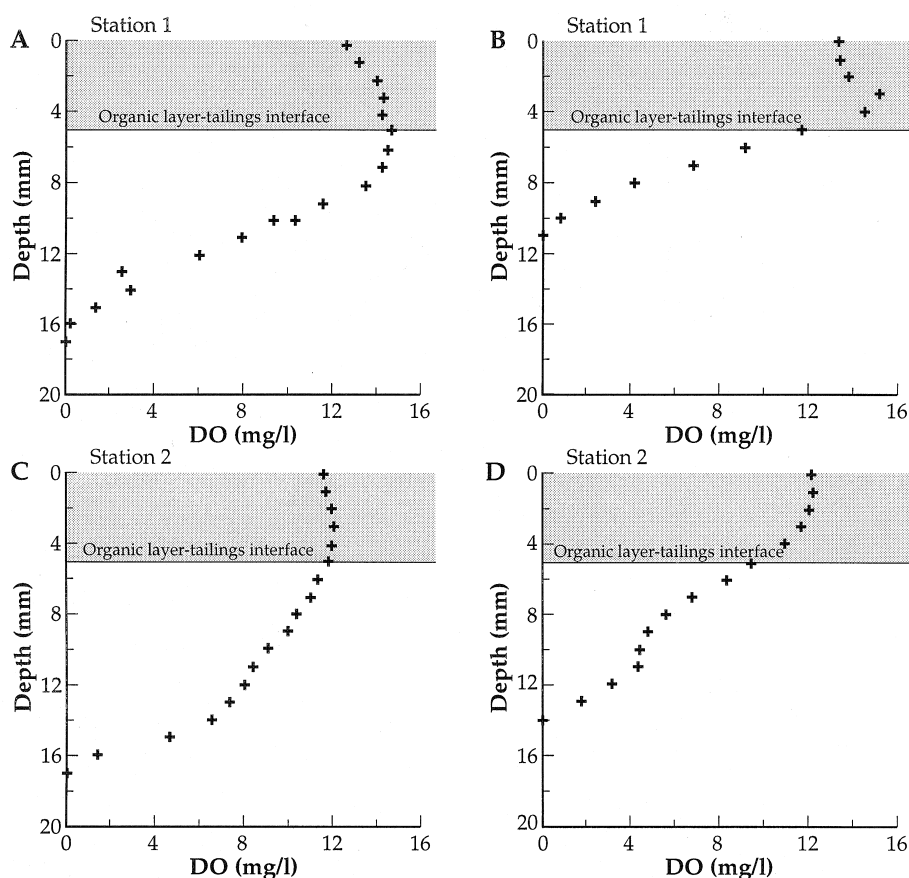


Fig. 3. Oxygen profiles measured in the cores from Stations 1 (a, b) and 2 (c, d). Depth scale in millimetres. Organic layer is shaded.

respectively, but the concentrations of the elements through the profiles vary more than the previous elements (Fig. 4d-f).

There are elements that have increasing concentrations with depth in the tailings. At Station 1 these elements are Mg, Si, Sr and Ba (Fig. 5a,d,f-g). There is a slight increase of total S, but not as pronounced (Fig. 5c). At Station 2 the elements are Mg, Ca, S, Si, Sr and Ba (Fig. 5a-d,f-g), almost the same elements as in Station 1. The behaviour of Ca and S at Station 1 is similar with maximum concentrations at 2.75 cm and rather constant concentrations throughout the profile below this depth.

5. Discussion

At both stations the concentrations of dissolved Cu, Zn, Cd, Ni, Mg, Si, Ba, Sr, Ca and S are higher in the pore waters of the tailings-water interface compared with the analyses of the pond bottom water. The concentrations are also higher compared with the pond

water sampled by Ljungberg et al. (1997). This concentration gradient between the uppermost pore water and the pond bottom water indicates that diffusion of metals may be occurring from the tailings into the overlying pond water (e.g., Elderfield and Hepworth, 1975). The same is valid for Co at Station 2. Lead at both stations and Co at Station 1, on the other hand, have concentration gradients that indicate diffusion from the pond water down to the tailings. The general trend is that the concentrations of metals in the tailings pore water are higher at Station 2 compared with Station 1, probably due to the fact that at this location previously oxidised tailings were deposited before the flooding (Ljungberg et al., 1997).

The dissolved concentrations of Mg, Si, Ba, Sr at Station 1 and of Ca, Mg, S, Si, Ba and Sr at Station 2, which have increasing concentrations with depth, can probably be explained by upward diffusion of trapped pore water which, in turn, may originate from old process water. The rate of diffusion will decrease due to wash out of these elements with time. It is reasonable to assume that the process water also contained metals

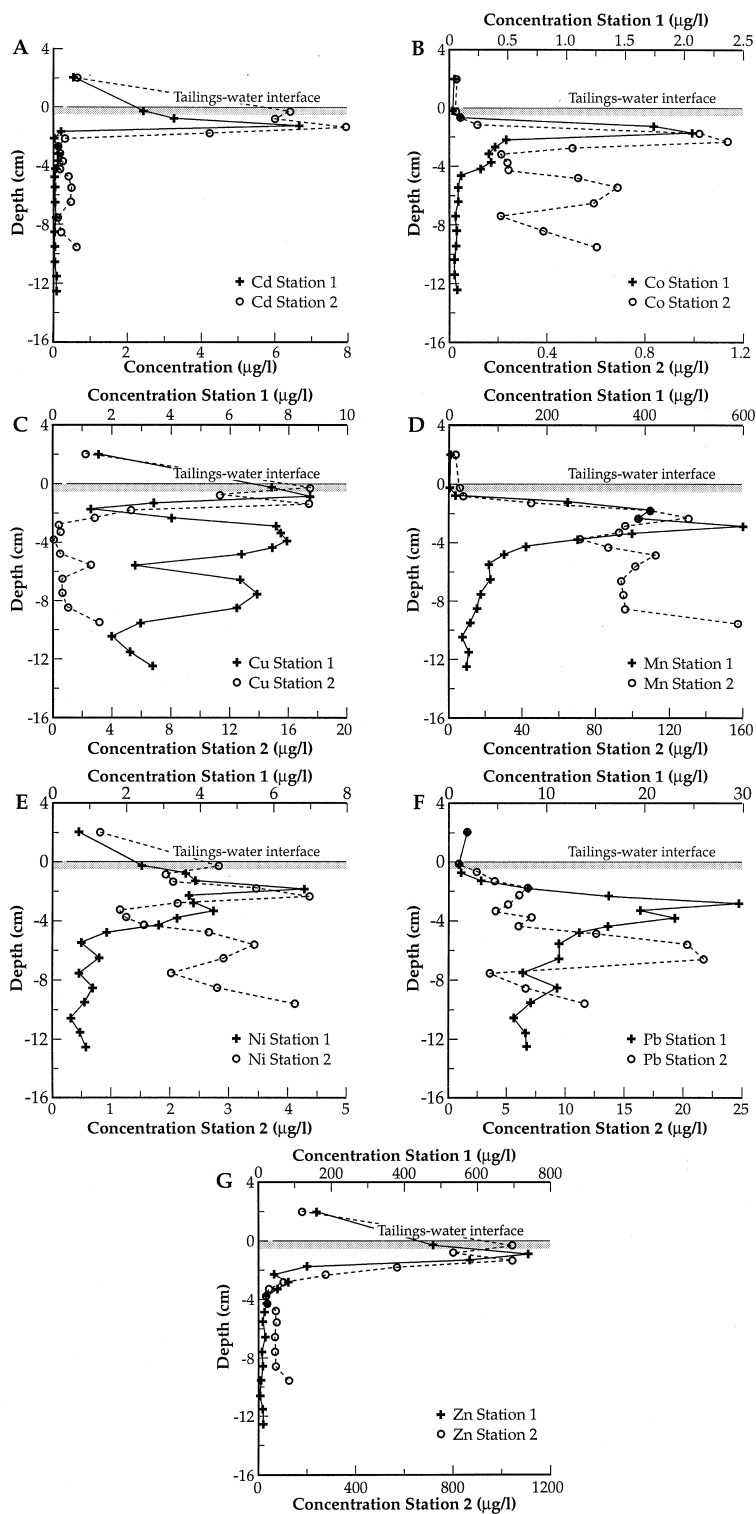


Fig. 4. Dissolved Cd (a), Co (b), Cu (c), Mn (d), Ni (e), Pb (f) and Zn (g) at Stations 1 and 2. Depth scale in centimetres. Organic layer is shaded.

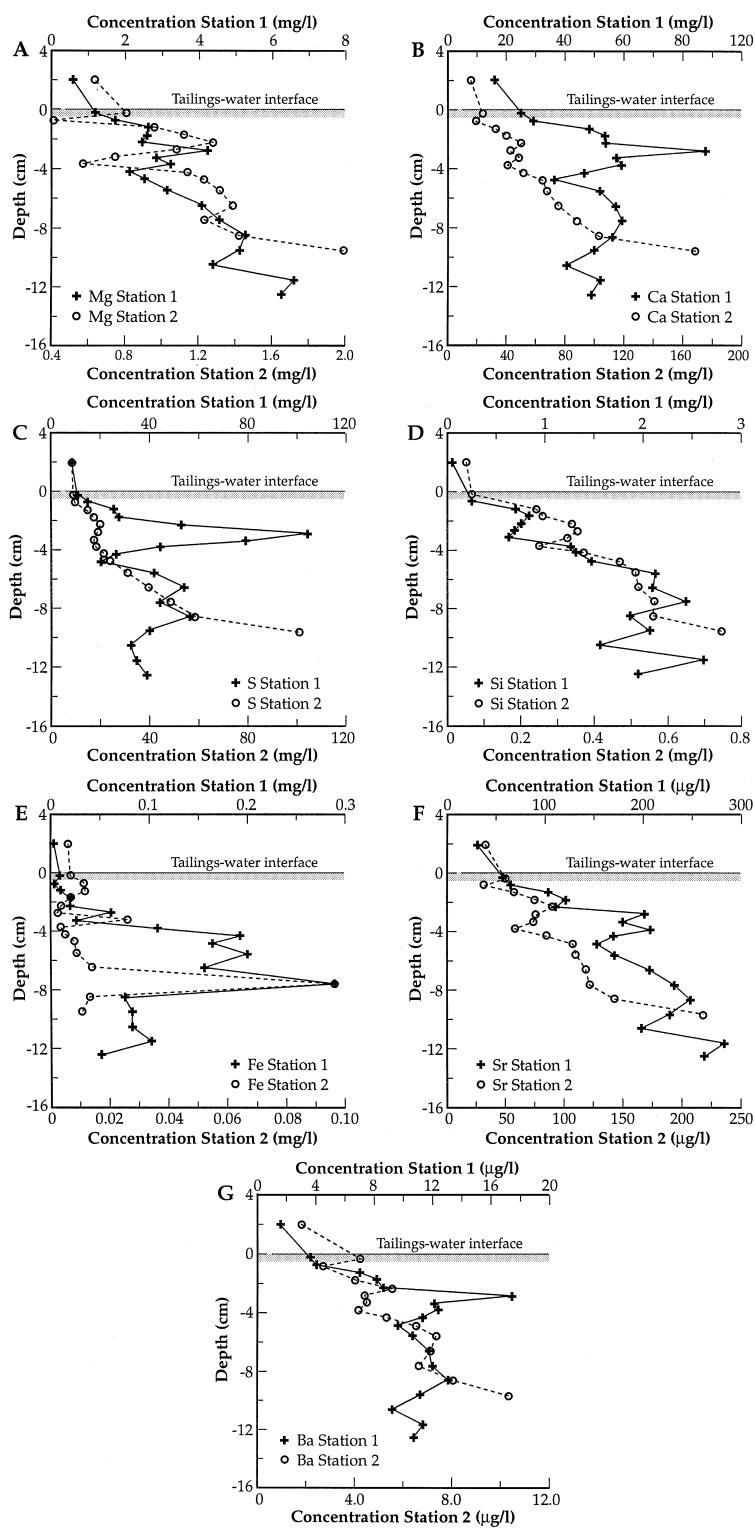


Fig. 5. Dissolved Mg (a), Ca (b), total S (c), Si (d), Fe (e), Sr (f) and Ba (g) at Stations 1 and 2. Depth scale in centimetres. Organic layer is shaded.

Table 2

Average pond water composition sampled 1995 from Ljungberg et al. (1997)

Element	Average pond water [concentration \pm s.d] 194 samples
[mg/l]	
Ca	20.0 ± 0.7
Fe	0.034 ± 0.008
K	0.42 ± 0.13
Mg	0.68 ± 0.05
Na	0.96 ± 0.13
S	11.1 ± 0.3
[μ g/l]	
Al	3.55 ± 0.70
As	0.28 ± 0.007
Ba	1.80 ± 0.20
Cd	0.69 ± 0.07
Co	0.15 ± 0.06
Cu	1.80 ± 0.30
Mn	17.9 ± 2.3
Ni	1.30 ± 0.30
Pb	0.17 ± 0.05
Sr	44.1 ± 1.4
Zn	139 ± 7.9

like Cd, Co, Cu, Ni, Pb and Zn but diffusion upwards of these metals is not supported by the pore water profiles (Fig. 4). This may be attributed to the fact that these elements are more immobile than, e.g., the alkaline earth metals at high pH, and are more easily adsorbed onto mineral surfaces at high pH (e.g., Kinniburgh et al., 1976; Kinniburgh and Jackson, 1981).

A well developed layer rich in Fe- and Mn-oxyhydroxides occurs at 0 to 1.5 cm depth (Fig. 6a-d). The peak of solid Fe is somewhat concealed at Station 2 since the tailings are rich in Fe due to the large pyrite content. However, Fe- and Mn-oxyhydroxides are unstable at low redox potentials (e.g., Ingri and Pontér, 1986; Widerlund and Ingri, 1996) and dissolve at depth, thereby increasing the content of dissolved Mn and Fe in the pore waters (e.g., McKee et al., 1989). Iron- and Mn-oxyhydroxides are also known to contain co-precipitated metals as well as adsorbed metals (e.g., Alpers et al., 1994; Tessier et al., 1996; Banks et al., 1997). When the oxyhydroxides dissolve these metals may be released into the pore waters, thereby increasing the metal concentrations (e.g., Shaw et al., 1990). At Stations 1 and 2, Fe- and Mn-oxyhydroxides are dissolving at depth where dissolved O_2 is being depleted as indicated, e.g., by the increasing concentrations of dissolved Fe between 4 to 8 cm at Station 1 and the increasing Mn concentrations between 1 to 4 cm at both stations.

It is probable that some of the Fe-oxyhydroxides that exist in the upper part of the tailings have formed due to sulphide oxidation followed by concurrent Fe-oxyhydroxide precipitation. Holmström et al. (1998) suggested that due to the high pH and carbonate content of the tailings at Stekenjokk, most of the Fe released from oxidation of sulphides in laboratory experiments rapidly precipitates as Fe-oxyhydroxides covering the sulphide surfaces. The occurrence of Fe-oxyhydroxides due to sulphide oxidation and carbonate buffering in the tailings at Stekenjokk has also been suggested by Ljungberg et al. (1997).

The heavy metal concentrations are high in the pore waters in the upper parts of the tailings at both Stations 1 and 2, which could be due to sulphide oxidation, despite the high pH of around 7.0 to 8.4 (Fig. 7). At these pHs most heavy metals should be adsorbed (e.g., Kooner, 1993; Coston et al., 1995) and the metal concentrations should be low. Since di- and trivalent metal ions are known to form complexes with humic- and fulvic acids (e.g., Schnitzer, 1986), the high concentrations might be explained by organic-metal complexing in the organic layer, which is composed of both organic material and sulphides, which may increase the metal concentrations. Another possibility could be that small colloids composed of, e.g., Fe- and Mn-oxyhydroxides are pressed through the filters during pore water extraction despite the small pore size of the filters used (e.g., Kennedy and Zellweger, 1974; Kimball et al., 1995).

The metal concentrations in the uppermost pore waters must originate from some process in the tailings. The water column of the pond or the deeper pore waters are not the metal source since they have much lower concentrations of most elements. If the only cause of the high heavy metal concentrations in the uppermost pore waters is adsorption/desorption on Fe- and Mn-oxyhydroxides the profiles should have been similar to the dissolved Mn and Fe profiles which they are not. There is no correlation between any element and Mn or Fe when studying all pore water analyses throughout the profiles except for the uppermost 3 analyses for Cd at station 1 and 4 analyses of Co at both stations. It is also unlikely that dissolution of Fe- and Mn-oxyhydroxides would occur within the zone where O_2 is available. Furthermore, since the maximum concentrations of dissolved Cd, Co, Cu, Ni, Pb and Zn are found in the upper centimetres of the tailings which are well oxygenated at both stations the most likely explanation for the high metal concentrations is sulphide oxidation.

Another indication of this reaction occurring is the relatively low pH of the pore waters in the upper layers of the tailings compared with deeper pore waters (Fig. 7). When some sulphides oxidise, H_2SO_4 is produced with a following decrease in pH. The pH of the

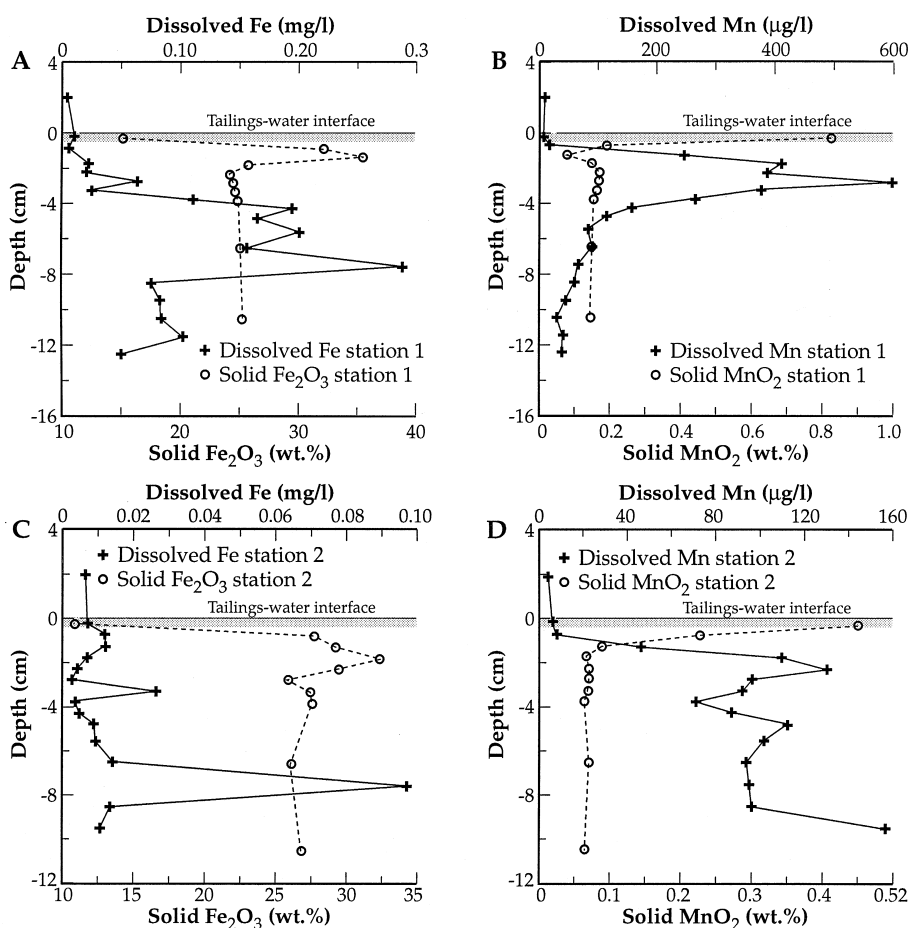


Fig. 6. Dissolved and solid Mn and Fe at Stations 1 (a–b) and 2 (c–d). Concentration of total Mn and Fe are expressed as Fe_2O_3 and MnO_2 . Depth scale in centimetres. Organic layer is shaded.

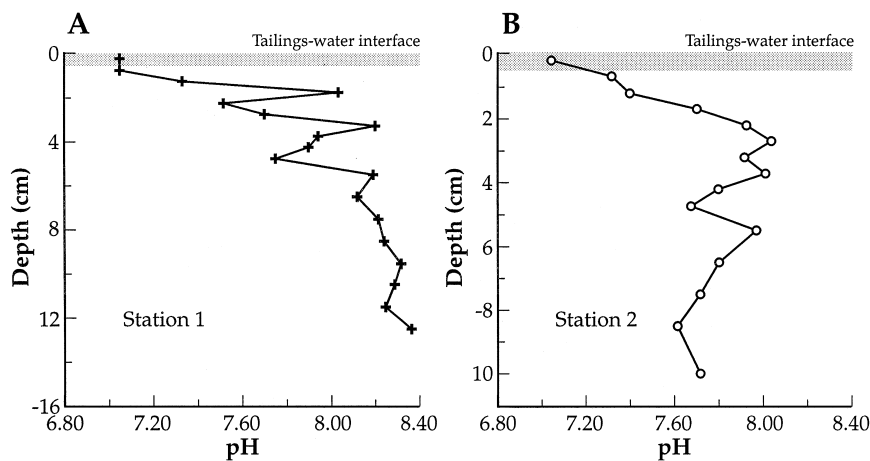


Fig. 7. pH of pore water at Station 1 (a) and Station 2 (b). Depth scale in centimetres. Organic layer is shaded.

pond water is between 7.57 and 7.78, but in the first 1.5 cm of the pore waters the pH varies between 7.04 and 7.33. At greater depth in the tailings the pore water pH increases to 7.7 to 8.4. Decomposition of organic material may also lower the pH, but since the organic layer is only about 0.5 cm thick, the low pH-values would be confined to this region and not deeper down.

It must be concluded that sulphide oxidation is the most likely reaction to occur in the upper parts of the tailings. The reasons are that the high heavy metal concentrations cannot be explained by downward diffusion of metals from the pond water or upward diffusion of older process water from the tailings. Dissolution of Fe- and Mn-oxyhydroxides is not the source for the metals. The upper part of the tailings is also well oxygenated and the pH is lower than in both the pond water and the deeper parts of the tailings.

6. Conclusions

There is a diffusion of dissolved elements from the tailings to the overlying water at Stekenjokk as a result of the concentration gradient between the pond water and the pore waters in the tailings. The presence of Ca, Mg, S, Si, Ba and Sr may be explained by diffusion of older process water trapped in the tailings. The concentrations of Cu, Zn, Ni, Co and Cd, however, cannot be explained by diffusion from the deeper parts of the tailings.

Oxygen concentrations in the tailings measured with microelectrodes show that there is plenty of O₂ in the pore water down to depths of 16 to 17 mm. Lower pH is also measured in the uppermost pore waters compared with the pond water and the tailings pore water at depth. High concentrations of heavy metals are measured in the upper parts of the tailings, which are interpreted to result from oxidation of sulphides at the tailings surface.

At Stekenjokk, a layer of organic material and Fe- and Mn-oxyhydroxide layers have developed at the surface during the 6 a since the flooding. The organic layer is increasing in thickness every year. The highest concentrations of dissolved metals are found at Station 2 where previously oxidised material was deposited before the flooding.

Flooding of tailings is a promising method for remediating sulphide-bearing tailings and at Stekenjokk it will probably work even better in the future. Despite minor oxidation today, the oxidation can be expected to decrease or even cease in the future due to O₂ consumption during decomposing of accumulating organic material. Metals eventually released from oxidising sulphide minerals may be trapped by the Fe- and Mn-oxyhydroxide barrier.

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