GEOCHEMISTRY OF SUBMERGED TAILINGS IN
ANDERSON LAKE, MANITOBA: RECENT RESULTS[1]

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Abstract: Sulfide-rich zinc-, copper-, and lead-bearing tailings have been deposited via floating pipeline into shallow (< 8 m) Anderson Lake in north-central Manitoba since 1979. The lake water contains elevated levels of dissolved metals which are derived mainly from an acid-generating roadway along the north shore. Water-column sampling and sediment coring were carried out through the ice on Anderson Lake in April 1993. Two sites were occupied, one proximal to the tailings discharge (Station B, the "pure tailings" site) and the other about 2 km away (Station A, the "natural sediments" site). Interstitial waters were extracted from duplicate cores collected at each location. The water column was strongly stratified at both locations, exhibiting four layers at the natural sediments site (two of which were dysaerobic or anoxic), and two layers near the tailings outfall, the lower being dysaerobic. The unusual multiple layering probably reflects the influence of laterally variable advective processes. High concentrations of dissolved iron in shallow pore waters indicate that the sediments at both locations were anoxic at shallow subsurface depths. Concentrations of Zn, Cu, Pb and Cd were very low or undetectable in the pore waters. There was no evidence of release of Cu, Cd or Pb from the deposited tailings, although there was evidence of possible minor release of Zn from surface sediments in one of the tailings cores. Metals were removed from pore waters below the upper 10 cm at both sites, which is attributed to precipitation of authigenic sulfide phases.

Additional Key Words: subaqueous disposal, diagenesis, sulfide.

Introduction

A growing body of information suggests that the permanent storage of unoxidized, sulfide-rich mine tailings under water and their eventual burial by natural sediments may serve to inhibit significantly the dissolution of metals from such deposits. This emerging view stands in marked contrast to terrestrial tailings disposal operations where combined chemical and biological oxidation of tailings often results in the generation of acidic, metal-bearing drainage. Subaqueous disposal offers promise as a waste management technique that minimizes the environmental effects of mining by inhibiting the release of dissolved metals to surface and ground waters. The most tenable hypothesis that accounts for this inhibition is that ambient oxygen concentrations within natural waters and sedimentary pore waters are too low to effect significant oxidation within the tailings deposit. Results from an increasing number of published studies of both marine and lacustrine subaqueous disposal operations support this hypothesis in general (e.g., Drysdale 1990, Pedersen 1983, 1985, Pedersen and Losher 1988, Pedersen et

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al., 1993); however, the basic tenet that tailings are essentially unreactive in submerged environments has not been fully established. Moreover, previous studies have not addressed the role of seasonal variations in hydrography and oxygenation on the reactivity of the submerged deposits. Recognizing that such seasonal effects are poorly understood, a program has commenced in which tailings reactivity is being investigated in detail in the winter and summer in Anderson Lake, Manitoba. In this paper, we present an abbreviated description of new results from the recent winter survey carried out in Anderson Lake, when the water column was rather remarkably stratified. A more comprehensive description and interpretation will be published elsewhere.

Environmental Setting and Background

Anderson Lake is located approximately 2 km south of the townsite of Snow Lake in central Manitoba (fig. 1). It is a small, shallow, highly productive (mesotrophic to eutrophic) Precambrian Shield lake, which was floored originally by organic-rich sediments (Pedersen et al. 1993). Since 1979, about 8 million t of tailings have been discharged at the surface, mostly to the western basin of the lake, via a movable, floating Sclair pipe.

Water quality in the lake is very poor (Pedersen et al. 1993), due to dissolved metals and salts being added from acid rock drainage issuing from an old roadway built of waste rock and tailings along the north shore of the lake. Dissolved solids are also added to a much lesser extent from the process water discharged from the pipeline.

Sampling and Methods

Two locations were sampled in April, 1993 (fig. 1), one (Station B) near the tailings outfall in nearly 4 m of water, and the other (Station A) some 2 km to the southeast. At both sites the water column was sampled by submerging in place a 3.8 m long plexiglass pipe studded with sampling ports. About 50 cm of ice was cut through with a gas-powered auger. At least 48 h after emplacement of the pipe, water samples were drawn through each port by peristaltic pumping at a rate slow enough (<1 mL/s) to minimize flow-field distortion. The samples were drawn into a nitrogen-filled glove bag to eliminate potential oxidation and immediately filtered through 0.45 μm polycarbonate membrane filters. Oxygen and temperature profiles were collected through a separate hole in the ice within 5 m of the water sampling location, using a YSI meter and submersible probe. The oxygen probe was field-calibrated with respect to air.

Duplicate cores for sediment and interstitial water analyses were collected through holes about 3 m apart and 5 m from the water column sampler at Station A,
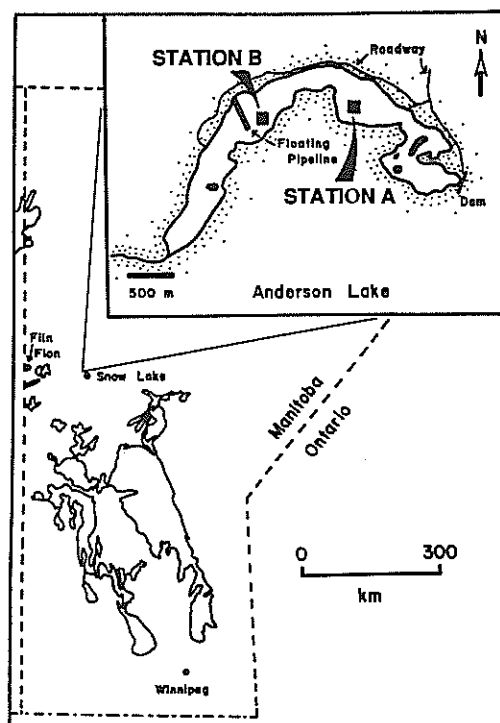

Figure 1. Lake and station locations.

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and about 12 m apart and ~10 m from the water column sampler at Station B. The lightweight gravity corer described by Pedersen et al. (1985) was used, and the quality of all four cores was excellent. Immediately after collection, each core was transported upright to nearby Snow Lake for processing. Interstitial water samples were extracted from the upper 30 cm of each of the cores by centrifugation under N_2 as described by Pedersen et al. (1993).

Analytical procedures for the interstitial water samples followed those described previously (Pedersen et al., 1993). Water column samples were analyzed by Analytical Services Laboratories (ASL) of Vancouver, as described by Maynard and Thomas (this volume). Sedimentary organic carbon (C_{org}), nitrogen, sulphur and $CaCO_3$ concentrations were determined at the University of British Columbia as described by Pedersen et al. (1993), while concentrations of a suite of major and minor elements in splits of the same homogenized sediment samples were measured by ASL (Maynard and Thomas, this volume).

Results

Water Column

Water column profiles of dissolved O_2 and temperature are shown in figure 2. Both the temperature and O_2 data at Station A indicate a four-layer stratification below the ice in April 1993. Relatively high O_2 contents (up to 4.6 mg/L) were limited to a cold water layer 20 cm thick immediately under the ice. The oxygen concentration decreased sharply between 60- and 80-cm depth, where the temperature increased from <1° to >6 °C. A mid-depth warm layer between 90 and 250 cm deep was characterized by a near-zero oxygen content. Up to ~1.5 mg/L O_2 occurred in a 1-m-thick aerobic zone near the bottom, which was slightly cooler than water in the mid-depth layer. Oxygen was again depleted in a warmer (by ~0.4 °C) 20-cm-thick layer adjacent to the bottom.

Less complex profiles characterize the water column near the tailings outfall at Station B (fig. 2). Oxygenated water was confined to a thin horizon immediately below the base of the ice and to the water in the 50-cm-deep hole through the ice, which must have been aerated (at both sites) when the holes were cut. As at Station A, the oxygen-depleted layer was much warmer than the relatively oxygenated waters above.

Variations in the concentrations of dissolved metals paralleled the stratification. Dissolved Fe contents, for
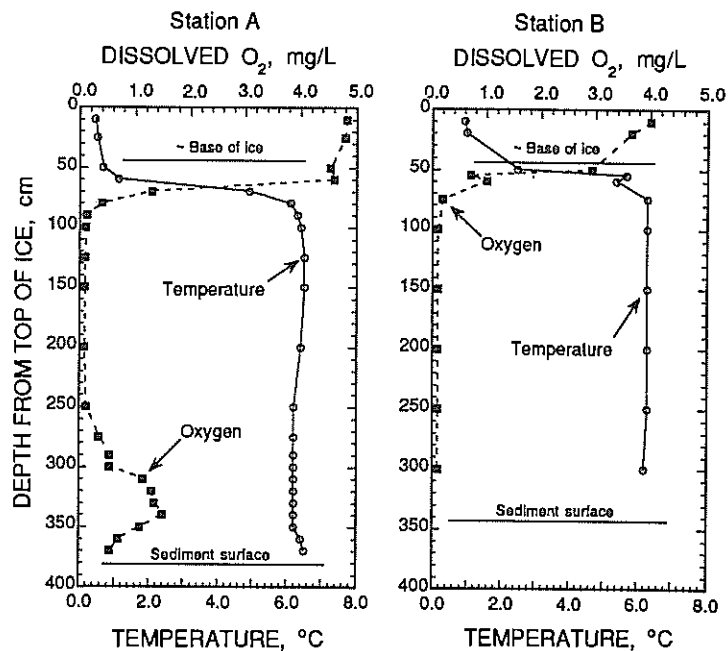
Figure 2. Oxygen and temperature profiles measured through the ice. Station locations are shown in fig. 1.

example were low (< 0.08 mg/L) in the oxic waters between 300- and 370-cm depth at Station A, but relatively high (up to ~9.5 mg/L) in the anaerobic layers (fig. 3). The oxygen-depleted waters at Station B hosted dissolved Fe contents of ~2 mg/L between 50- and 250-cm depth; below this horizon, the concentrations increase steadily and markedly toward the bottom, reaching ~70 mg/L in the deepest sample.

The distribution of dissolved Zn in the water columns at both sites was antipathetic to that of Fe; high Zn values of up to ~400 mg/L occurred where iron contents were low, and diminished sharply in the Fe-rich intervals (fig. 3). The contrast between the two elements was particularly pronounced in the lower 20 cm at Station A where abrupt changes in both the Fe and Zn contents occur 10 cm above the bottom.

Arsenic distributions in the water column were very similar to those of iron at both sites, although the absolute As concentrations near the tailings outfall (0.3 to 0.6 mg/L) were only about one-third of those at the natural sediments site (fig. 3).

Sediments and Interstitial Waters

Cores A1 and A2 collected ~3 m apart at the natural sediments site were visually and compositionally very similar. Both cores were veneered by a 2- to 3-mm-thick cap of rusty-brown noncohesive fine-grained sediment which contained abundant organic fragments. Small copepods (Daphnia?) were abundant in the water immediately above the sediment-water interface and were observed burrowing into the rust-colored surface layer. The surface veneer was underlain by about 10 cm of charcoal-gray fine-grained gelatinous ooze, which graded into the brown, gelatinous, homogeneous, organic-rich ooze that characterized the lower 40 cm of both cores. Small (presumably) methane bubbles developed below 30 cm depth in both cores shortly after collection. Both cores raised about 12 m apart at Station B consisted of undifferentiated fine-grained gray tailings which contained a very high proportion of glistening, very fresh-looking pyrite grains. The lake floor at this location was irregular with differences of more than 1 m depth between sites only 12 to 15 m apart. Observations made by divers during the
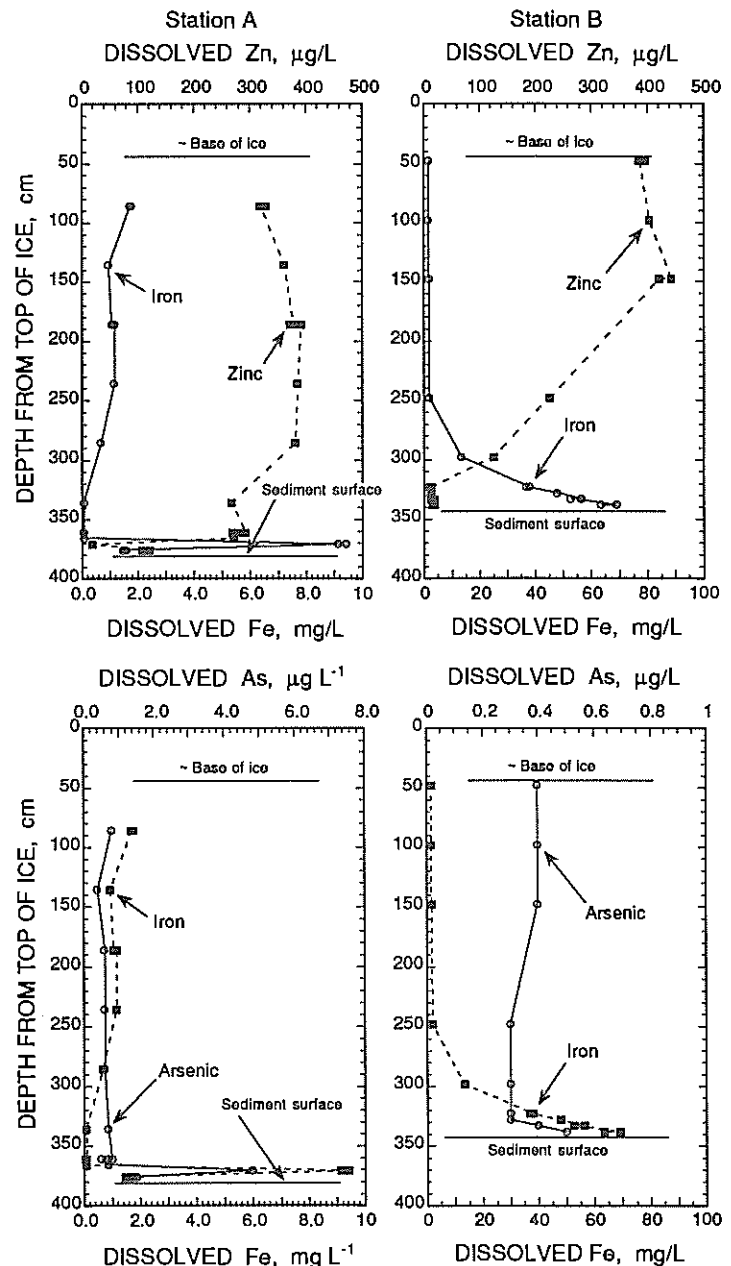

Figure 3. Dissolved iron, zinc, and arsenic profiles in the water column at the two sampling sites.

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August 1993 survey of the lake confirmed that the sediment surface near the tailings outfall is hummocky. Lobes of tailings appear to account for the observed differences in local relief.

Cores A1 and A2 consist of essentially tailings-free, organic-rich sediments below about 12 cm deep, as shown by C_{org}, Fe/Al, S, Zn, Cu, Pb, As, and Cd data (not shown, but the distributions are very similar to those reported by Pedersen et al. 1993). The upper stratum in both cores is composed of a mixture of tailings and natural sediments with metals concentrations reaching maxima between 1- and 2-cm depth. The marked compositional similarity of cores A1 and A2 is not matched by the pair of cores from Station B. Organic carbon, Fe/Al, S, Zn, Cu, Pb, As, and Cd distributions in cores B1 and B2 show differences with depth, which apparently reflect significant local-scale lateral inhomogeneities in the tailings deposit in the lake. This inhomogeneity is not inconsistent with the variable composition of the ore feedstock and the frequent changing of the location of the discharge outfall.

All filtered pore water samples from all four cores were analyzed for a suite of dissolved metals. We report here the distributions of Fe, Mn, Zn, Cu, Pb, and Cd. Total dissolved sulfide was measured in selected aliquots where volume permitted.

Dissolved Fe profiles are shown in figure 4 along with concentrations measured in the lowermost sample (5 cm above the bottom) collected with the water column sampler. The "duplicate" profiles are similar in form at each site: high concentrations characterize the pore waters in the upper several centimeters, particularly in the Station B cores; below the upper 10 cm, concentrations fall to very low values. Dissolved Mn distributions are fundamentally different (fig. 4): there is no significant increase with depth in the upper 10 cm, and there is no depletion toward the base of the cores as is evident for iron. Dissolved zinc concentrations at the natural sediments site sharply decrease with depth in the upper 2 cm of the deposits (fig. 5), similar to the tailings in core B1, whereas in B2, a peak in concentration (~25 μg/L) occurs between 0.5 and 2 cm depth.

Dissolved copper (fig. 5) was essentially undetectable (≤ 0.12 μg/L) in all pore waters extracted from the pure tailings cores (as well as in the overlying bottom water). In cores A1 and A2,
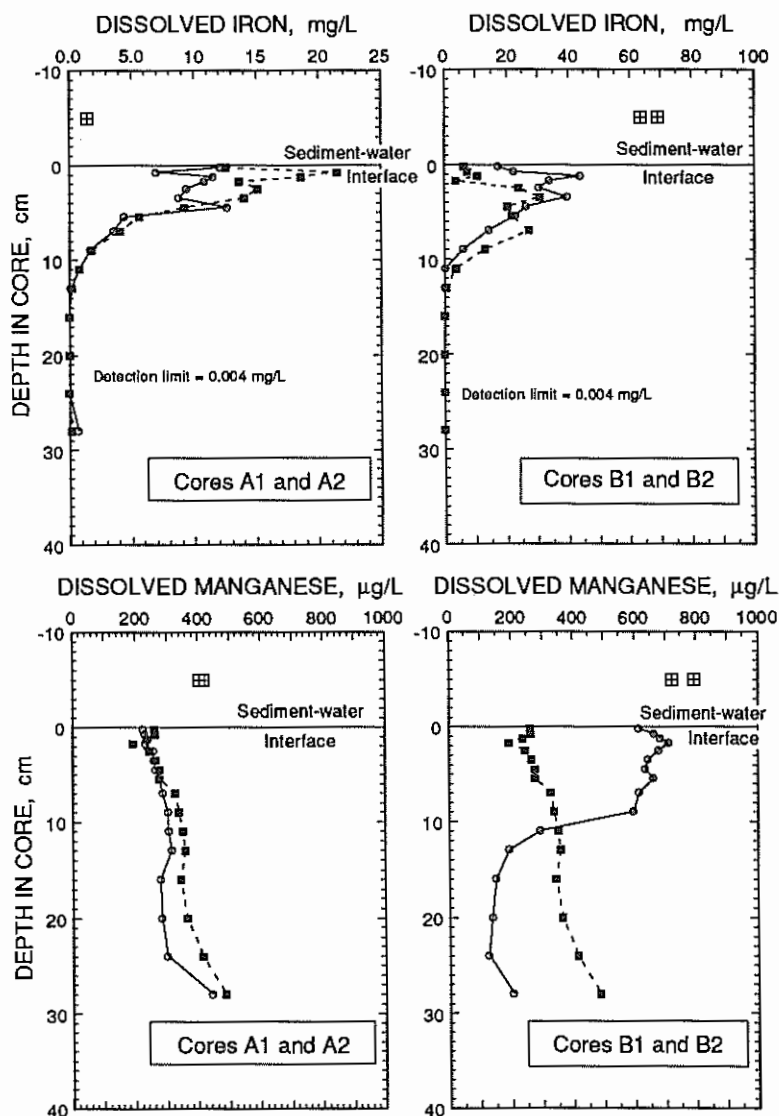

Figure 4. Dissolved interstitial iron and manganese distributions in duplicate cores from the sampling sites. Cores A1 and B1 are designated by open circles, and A2 and B2 by open squares.

maximum concentrations of 2.8 µg/L are observed in the upper 2 cm, with very low or undetectable values at greater depths. Neither Pb nor Cd was detectable in any of the pore water samples at either station (fig. 6), excepting the 1.25-cm sample in Core A1 where the Cd concentration marginally above the detection limit. Lead and cadmium were primarily undetectable in the bottom waters at either site. Dissolved sulfide was not detectable in pore waters from the tailings cores, in contrast to the measurable but low levels (up to 25 µmol/L) recorded at the natural sediments site (fig. 7). The decline in dissolved sulfate concentration with depth in the natural sediments is consistent with the sulfide profile. Increases in interstitial sulfate with depth at the tailings site (Station B, fig. 7) indicate that the tailings release sulfate to pore waters; Pedersen et al. (1993) attributed this to dissolution of sulfide alteration products formed during milling, and pointed out that the addition of sulfate to the pore waters at depth does not rule out the co-occurence of sulfate reduction.

Discussion

Pedersen et al. (1993) described the distribution of dissolved metals in pore waters collected in summer 1990 at three sites in Anderson Lake. Their principal conclusion was that the submerged deposited tailings in Anderson Lake were not releasing metals to the overlying water column at that time. Indeed, the opposite appeared to be true: sharp decreases with depth in the concentrations of dissolved Zn, Cu, Pb, and Cd in the upper few centimeters of the deposits were interpreted as representing consumption of metals from the contaminated overlying lake water. Precipitation of authigenic sulfide phases at shallow depths in anoxic tailings and natural sediments was suggested as an explanation for the very low metals concentrations in the pore waters.

The winter survey results presented here confirm that the water column in Anderson Lake undergoes a pronounced seasonal change in hydrography and chemistry. When the lake is ice covered and wind-driven mixing is eliminated, the development of water column anoxia appears likely. We do not know how long such a water-column condition might persist in any given year nor whether episodes of anoxia or dysaerobia recur annually. However, the contrast in water column stratification
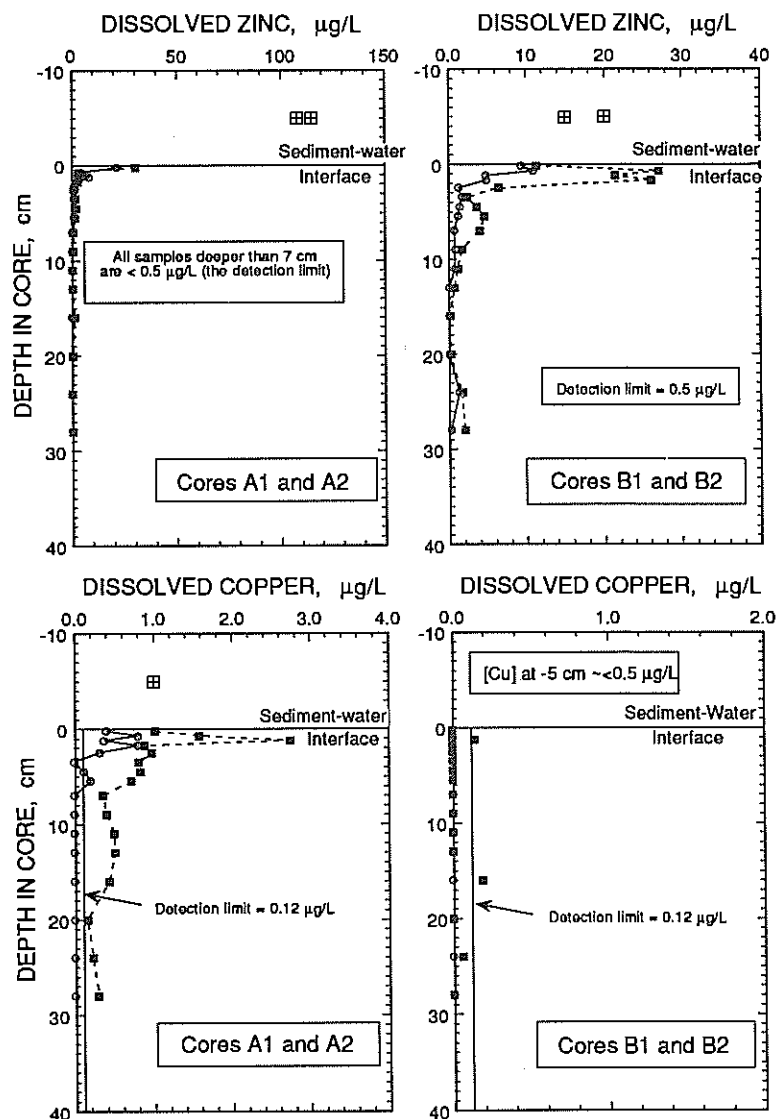

Figure 5. Dissolved zinc and copper distributions in duplicate cores. Symbols as in fig. 4.

between the 1990 summer survey, when the water column was warm and oxygen replete, and the wintertime observations presented here suggests that the conclusions of Pedersen et al. (1993) are applicable to the summer season only.

Several conclusions can be drawn from these preliminary results. First, steady state does not exist in Anderson Lake as it might in deeper water bodies; this complicates the interpretation of chemical exchange between the sediments and the overlying waters. The seasonal development of a multilayer stratification, which appears to vary both horizontally and vertically, adds additional complexity. Despite these difficulties, these data indicate that there was no measureable release of dissolved Cu, Pb, or Cd from the rapidly-deposited tailings near the floating outfall in early April 1993, despite the tailings being highly enriched in each of these metals. Similarly, there was no apparent release of dissolved Cd or Pb from "natural" but tailings-contaminated sediments" cored at Station A.

Second, although anaerobic water occupied almost three-quarters of the water column at Station A, a thin layer of oxygenated water was present in the lower meter. This poses a thermodynamic conundrum in that occurence of the high dissolved iron content observed 10 cm above the bottom is inconsistent with the presence of O₂ in the same water. We have no obvious explanation for this observation. The water-column Fe profile (fig. 3) indicates that the Fe spike could not have originated from reductive dissolution of Fe oxyhydroxides in the underlying sediments at the sampling site. Also, the spike could not be due to slow oxidation of Fe^{2+} at a low pH because the pH measured in the iron-rich interval was ~7.5. However, the high dissolved As content at the same horizon 10 cm above the bottom does imply that oxyhydroxide dissolution is responsible for the Fe peak, since arsenate ion readily adsorbs to FeOOH and is released when the latter dissolves under anoxic conditions (Belzile and Tessier 1990). Thus, we speculate that the thin iron- and As-rich layer could have had been produced at a nearby location and was advected laterally to Station A. If such phenomena are indeed active in the lake, than any comparison of the bottom-water metals concentrations with core-top pore waters becomes problematic: neither chemical nor compositional continuity would exist between the pore and
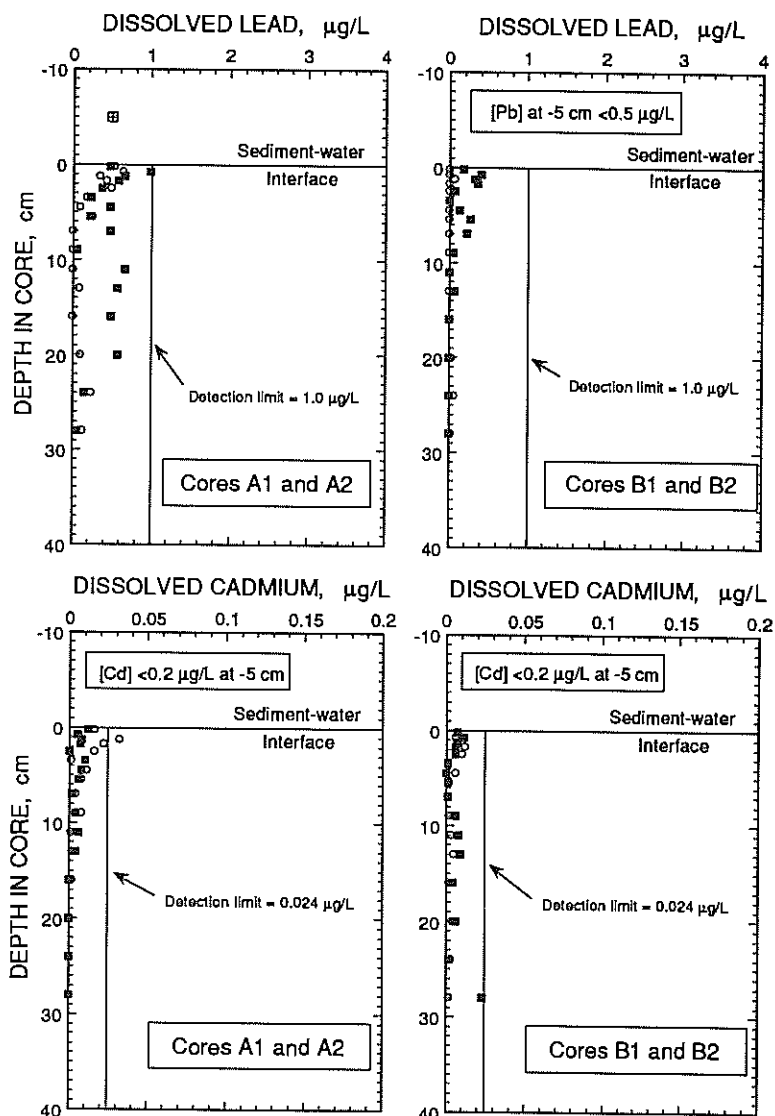

Figure 6. Dissolved lead and cadmium distributions in duplicate cores. Symbols as in fig. 4.

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bottom waters under these circumstances. This implication might explain the contrast between the high iron concentration in the bottom water at Station B (fig. 3) and the minimum in the pore water Fe profiles seen at the surface in both cores raised from this site (fig. 4).

The high iron content observed in the near-surface pore waters at Station A may be attributed to reductive dissolution at shallow depths in the sediment column; this is consistent with the presence of the thin rusty-brown veneer on the core tops at that site, and the black colour of the immediately underlying deposits. The steep decline in dissolved Fe below about 5 cm depth in both cores plainly reflects precipitation of FeS or FeS_2. As noted earlier, free dissolved sulfide is present in the pore waters in both cores below the upper several centimeters (fig. 7).

Third, although the data from the tailings site (Station B) unequivocally indicate no copper release to the overlying water, the profiles in the "natural sediments" (Station A) imply that Cu was being released to pore solution at about 1.25 cm depth and was diffusing both upward and downward from this maximum. More problematic is the subsurface dissolved zinc maximum seen in core B2, which is shallower than the pore water Fe maximum in the same core. Although

Figure 7. Dissolved sulfide and sulfate distributions in duplicate cores. Cores A1 and B1 are indicated by circles and A2 and B2 by squares.

this distribution could reflect a diffusive efflux of Zn out of the tailings, the maximum may be somewhat artificial: a change in the bottom water zinc content not long before the cores were collected could have induced a perturbed profile that does not reflect steady-state diagenesis. An additional ambiguity is that the tailings were overlain by oxygen-poor water in April 1993, and under such conditions, no Zn should be released (for example, via oxidation of the surfaces of ZnS particles). The spatial disparity between the dissolved zinc and iron maxima in the shallow pore waters of Core B2 tends to rule out iron oxyhydroxide dissolution as an explanation for the apparent zinc release. On balance, we prefer non-steady state perturbation as a possible explanation for the zinc efflux implied by the dissolved Zn data in the upper centimetre of Core B2. The principal implication of this suggestion is that temporally-varying chemical reactions and hydrographic processes in the overlying water column may play a major role in dictating the distributions of dissolved metals in the near-surface pore waters.
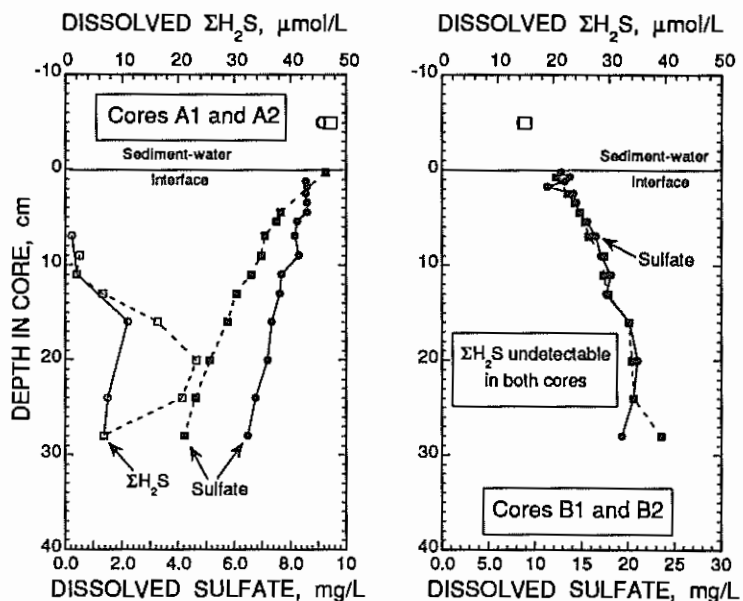
Summary and Implications

Pedersen et al. (1993) noted that Anderson Lake is essentially a sediment-starved basin, but it is also mesotrophic to eutrophic in character. Thus, the natural flux of sediments to the bottom of the lake is characterized by little silicate detritus and an extremely high organic content. Therefore, anoxia develops at very shallow subbottom depths. Mine tailings are now widely distributed on the floor of the lake, and

all available results are consistent in indicating that no Cd, Pb or Cu is being released from the submerged tailings. Unlike the summertime survey of Pedersen et al. (1993), however, the winter survey data discussed here do not rule out the possibility that there was a very small efflux of dissolved zinc from the tailings to the overlying water in April 1993.

These results confirm that metal release from fresh, sulfide-rich tailings is limited by submerged storage, in contrast to the behavior of sulfide-bearing tailings deposits stored subaerially. Along the north shore of Anderson Lake, subaerial tailings deposits have become acidic and are releasing substantial quantities of metals to surface drainage.

Acknowledgments

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