GEOCHEMICAL ASSESSMENT OF SUBAQUEOUS TAILINGS DISPOSAL IN ANDERSON LAKE, SNOW LAKE AREA, MANITOBA

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Geochemical Assessment of Subaqueous Tailings Disposal in Anderson Lake, Snow Lake Area, Manitoba

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EXECUTIVE SUMMARY

Available evidence suggests that the post–depositional (diagenetic) chemical reactivity of mine tailings is inhibited by storage under water, and implies that such storage may provide a preferred long–term disposal option for such wastes. To assess this, we examine in this report the chemistry of interstitial waters and the associated solid phases in tailings and natural sediments in Anderson Lake, near Snow Lake, Manitoba. Anderson Lake has been used as a receiving basin for tailings since 1979. Tailings are areally widespread in the lake, despite discharge being confined to the western side.

Three cores were collected in June 1990, and processed under nitrogen to extract interstitial waters. Solid–phase chemical measurements indicate that two of the cores penetrated though metal– or tailings–rich zones into underlying, pre–mine, organic–rich (20 to 30 wt. % C) natural deposits; the third consisted essentially of pure tailings. At all sites, dissolved iron measurements made on the pore water samples indicate that the deposits are anoxic at very shallow depths, within several millimetres of the sediment–water interface. This reflects the high oxidant demand of the sediments at all locations, and/or the physical effect of rapid accumulation of tailings which limits the penetration depth of O_2 via downward–diffusion, given the short residence time of a specific horizon near the interface.

High dissolved Zn, Cu and Pb concentrations in supernatant water confirm measurements made previously that Anderson Lake water is elevated with respect to these metals. The concentrations of all three elements decrease abruptly with depth in the cores at all three locations, however. This cannot be due to non–steady–state effects and indicates unequivocally that both the tailings and natural sediments are acting as sinks for metals, rather than as sources. Presumably, the metals are being precipitated as sulphide phases at shallow depths. Sulphate reductions with consomitant production of HS– is expected, given the evidence for very shall anoxia in the deposits.

It is clear that the deposited tailings are not releasing metals to the overlying lake water at present. In the post–discharge future, the tailings will be progressively covered by a blanket of organic–rich natural sediments which will act to preserve the anoxic conditions, now extant, essentially in perpetuity. Thus, it is unlikely that the tailings on the lake floor will ever support a benthic efflux of metals to Anderson Lake water.

SOMMAIRE

Les données disponibles indiquent que la réactivité chimique après dépôt (diagénétique) des résidus miniers est inhibée lorsque les résidus sont entreposés sous l'eau et qu'un tel mode d'entreposage pourrait être une meilleure solution pour l'élimination à long terme de ces déchets. Pour vérifier cette affirmation, nous examinons dans le présent rapport la composition chimique des eaux interstitielles et les phases solides associées dans les résidus et les sédiments naturels du lac Anderson, près de Snow Lake au Manitoba. Le lac Anderson a été utilisé comme bassin de réception de résidus depuis 1979. Les résidus sont très dispersés dans le lac, même s'ils n'ont été rejetés que dans la partie occidentale.

Trois carottes ont été prélevées en juin 1990, puis traitées à l'azote pour en extraire les eaux interstitielles. Les mesures chimiques pratiquées sur la phase solide indiquent que deux des carottes traversaient des zones riches en métaux et en résidus pour pénétrer dans les dépôts naturels sous-jacents, riches en matière organique (de 20 à 30 % C en poids), qui sont antérieurs aux résidus miniers; l'autre carotte consistait essentiellement en des résidus purs. Aux trois points d'échantillonnage, le dosage du fer dissous dans les échantillons d'eau interstiticielle indique que les dépôts sont anoxiques aux très faibles profondeurs de l'ordre de quelques millimètres sous l'interface sédiments-eau. Cela traduit une forte demande des sédiments en oxydant aux trois endroits et (ou) l'effets physique de l'accumulation des résidus qui limite la profondeur de pénétration de l'oxygène par diffusion vers le bas, compte tenu du faible temps de séjour d'un horizon particulier près de l'interface.

Les concentrations de Zn, de Cu et de Pb dissous dans l'eau surnageante confirment les mesures antérieures selon lesquelles les concentrations de ces métaux sont élevées dans l'eau du lac Anderson. Les concentrations des trois éléments diminuent soudainement avec la profondeur dans les trois carottes prélevées. Cela ne peut être attribuable à des effets d'un régime non permanent et indique sans équivoque que les résidus et les sédiments naturels agissent comme des pièges plutôt que comme des sources de métaux. Il y a probablement précipitation des métaux sous forme de sulfures à de faibles profondeurs. La réduction du sulfate et la production concomittante de HS- sont à prévoir, à cause de l'anoxie dans les dépôts à très faible profondeur.

Il est clair que les résidus déposés ne libèrent pas actuellement des métaux dans l'eau sus-jacente du lac. Dans l'avenir, après les rejets, les résidus seront progressivement recouverts d'une couche de sédiments naturels riches en matière organique qui tendra à maintenir indéfiniment les conditions anoxiques actuelles. Il est donc probable que les résidus sur le fond du lac empêche tout passage benthique de métaux dans les eaux du lac Anderson.

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UBC personnel were invaluable to the success of the project and included Bert Mueller who provided field assistance and analytical expertise in the laboratory; Jay McNee who carefully performed the dissolved metals measurements; Maureen Soon and Mark Noyon, who carefully and expeditiously prepared samples and made all XRF, CNS, CHN, and coulometer analyses.

We are very grateful to Pat Davidson at Hudson Bay Mining and Smelting Ltd. (Snow Lake) for supplying us with excellent laboratory facilities in the kitchen of the mine cafeteria as well as accommodation. Mickey Fey and Bill Salahub of HBMS kindly provided us access to the mine's pontoon boat which was used for the coring and water sampling operations.

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1.0 INTRODUCTION

The disposal of large volumes of sulphide-rich mine tailings at depth in marine and lacustrine basins is increasingly being considered as an option for permanent storage of such deposits. Implicit in this consideration is the perception that, given certain conditions, tailings may not release metals to the overlying waters at levels which could cause environmental degradation. This perception is based both on theoretical considerations (summarized in Rescan 1989) and on a limited number of published studies of the post-depositional (i.e. diagenetic) chemical behaviour of tailings in several active or abandoned deposits located mostly in western Canada (e.g., Drysdale 1990, Pedersen 1983, Pedersen 1984, Pedersen 1985, Pedersen and Losher 1988, Pedersen et al. 1990, Rescan 1990b and Rescan 1990c). These accrued results illustrate reasonably well the extent to which tailings react given specific depositional conditions; however, the important task remains of determining the degree to which the extant studies can be used to predict diagenetic responses in future disposal schemes or in deposits which have been abandoned for variable lengths of time. Thus, there is a well-defined need for quality information on the long-term diagenetic activity of mine wastes, both in marine and lacustrine waters. Toward this end, in this report we present the results of a detailed investigation of the chemical behaviour of Zn, Cu and Pb in tailings discharged to the floor of Anderson Lake, Manitoba. This study complements a concurrent investigation of submerged, abandoned tailings in Mandy Lake near Flin Flon, Manitoba (Rescan 1990b).

1.1 Background to the Study

A brief historical overview is presented here, which includes results the recent investigation by Rescan (1990a). Prior to the commencement of tailings disposal in 1979, Anderson Lake was used as a water supply for the adjacent Anderson mine. The lake currently receives drainage from the since shut-down Anderson mine area. Oxidized mill-tailings have been used to build roads along the north side of the lake. Drainage from these tailings and from the mine site is acidic and has had deleterious effect on adjacent vegetation. Recreational use of the lake is, and has been, minimal as the lake has been regarded by local people as dead. A typical small, shallow

Precambrian Shield lake, Anderson Lake highly productive and is floored by organic-rich sediments. The lake historically has contained few fish.

Several limnological surveys of varying degrees of detail were conducted on Anderson Lake prior to tailings deposition (Allard 1965, Munro and Ruggles 1977, Bridges 1977). Allard (1965) collected limited water quality, fisheries and benthic invertebrate data as part of an assessment of the suitability of the lake for introduced exotic game fish. No fish were caught in gill nets but brook sticklebacks (*Culaea inconstans*) were caught using Rotenone. Dredge sampling indicated low numbers of invertebrates including amphipods, chironomids, *Chaoborus*, snails and sphaerid clams. Water quality analyses indicated the lake had an average pH of 6.8 to 7.4, dissolved oxygen levels ranging between 5.4 to 14.0 ppm, bicarbonate alkalinity (1.9 to 2.7 mg/L as $CaCO_3$) and secchi disk transparency of 1.3 m.

Prior to tailings deposition, Hudson Bay Mining and Smelting Co. Ltd. (HBMS) studied physical and chemical limnology, benthos, zooplankton, phytoplankton, and fish (Bridges 1977). The lake was described as essentially land-locked, receiving minimal input from surface runoff, swamp drainage and precipitation. The maximum and mean depths were respectively given as 7.0 and 2.4 m. Water quality data collected in May of 1977 included pH (8.1 to 8.3), dissolved oxygen (9.9 to 11.1 ppm), conductivity (225 to 250 μmhos cm^{-1}), turbidity (1.2 to 1.9 NTU), secchi disk transparency (1.0 to 1.5 m), and other parameters (chloride, sulphate, S_2O_3 and alkalinity). Six water stations were sampled for dissolved metals (Cu, Zn, Fe, Pb, Ca, Cd, Mg, Ni and Co); concentrations of these elements were similar to those in other Precambrian Shield lakes. Bottom sediments were sampled at four stations and analyzed for specific metals (Al, Cu, Zn, Fe, Pb, Cd and Hg), silica and loss on ignition.

A net tow revealed the presence of a plankton community dominated by rotifers and diatoms. Of the four stations sampled for benthic macroinvertebrates only one station had any invertebrates (13 chironomids). No fish were caught in the gill nets, but lake chub (*Couesius plumbeus*) and brook stickleback were caught in minnow traps.

The lake was classified in 1977 as being as mesotrophic approaching eutrophic, and was predicted to become more eutrophic due to natural causes. The recent survey by Rescan (1990a) indicates that the lake is currently mesotrophic. Benthic invertebrate densities are low but comparable to previous observations; dominant benthic organisms are *Chaoborus*, chironomids, snails and clams. Zooplankton densities are highly variable, being lower near the tailings discharge, but the diversity is similar to that seen in other Manitoba lakes. Fish are rare in the lake, which has never supported a sport fishery.

Since the start up of the Snow Lake mill in 1979, HBMS has conducted regular water quality surveys of Anderson Lake. These surveys were conducted two or more times per year between 1979 and 1985 for various selected parameters which regularly included pH, suspended solids, turbidity, sulphate, copper and zinc. Other parameters measured irregularly included thiosalts, acidity/alkalinity, dissolved oxygen, secchi disk transparency, chloride, lead, nickel, cadmium, conductivity, and H_2S. Sampling has occurred periodically since 1986 for metals, pH, and suspended solids.

Anderson Lake currently receives high sulphide tailings from the Snow Lake mill operated by Hudson Bay Mining and Smelting Co. Ltd. (HBMS). The mill, rated at 3,450 mtpd, receives various copper-lead-zinc ores from four underground mines in the surrounding area. Since 1979, about 8 million tonnes of tailings have been deposited into the lake. Discharge is at the surface via a movable, floating Sclair pipe (30 cm diameter). The disposal location varies seasonally with shallower depths (3 m) being selected in the summer and greater depths in the winter (up to 6 m). This system prevents buildup of tailings in any one area and helps to maintain a water depth of 0.6 m over the deposited tailings. Tailings initially deposited in the lake maintained a 25 - 30° angle of repose, and did not readily disperse due to the quiescent lake conditions and the sharp drop from the discharge outfall. At start-up, the tailings built up above the lake surface and had to be moved in order to keep the deposits submerged. Anderson Lake is recognized, within a regulatory context, as a tailings and waste water disposal area. Control limits are placed on the discharge from Anderson Lake. These limits have been met since tailings pond start-up in 1979.

The tailings consist of silicate gangue minerals, predominantly quartz and feldspar, with minor hornblende, chlorite, epidote, some carbonate, and traces of other silicate minerals, and abundant pyrite with accessory pyrrhotite, sphalerite and minor chalcopyrite and arsenopyrite (Rescan 1990a). Framboidal pyrite occurs as a trace constituent, often in association with organic matter (Rescan 1990a).

2 - Study Area and Methods

2.0 STUDY AREA AND METHODS

2.1 Study Area

Anderson Lake is located in central Manitoba, approximately two kilometres south of the townsite of Snow Lake (Figure 2-1). As noted above, the lake is an active subaqueous tailings disposal site. Discharge was proceeding normally during the fieldwork carried out for this project in late June, 1990, with the exception that a significant body of tailings had built up above the lake level. These deposits were directly exposed to the atmosphere, but appeared to be unoxidized.

2.2 Sampling Stations

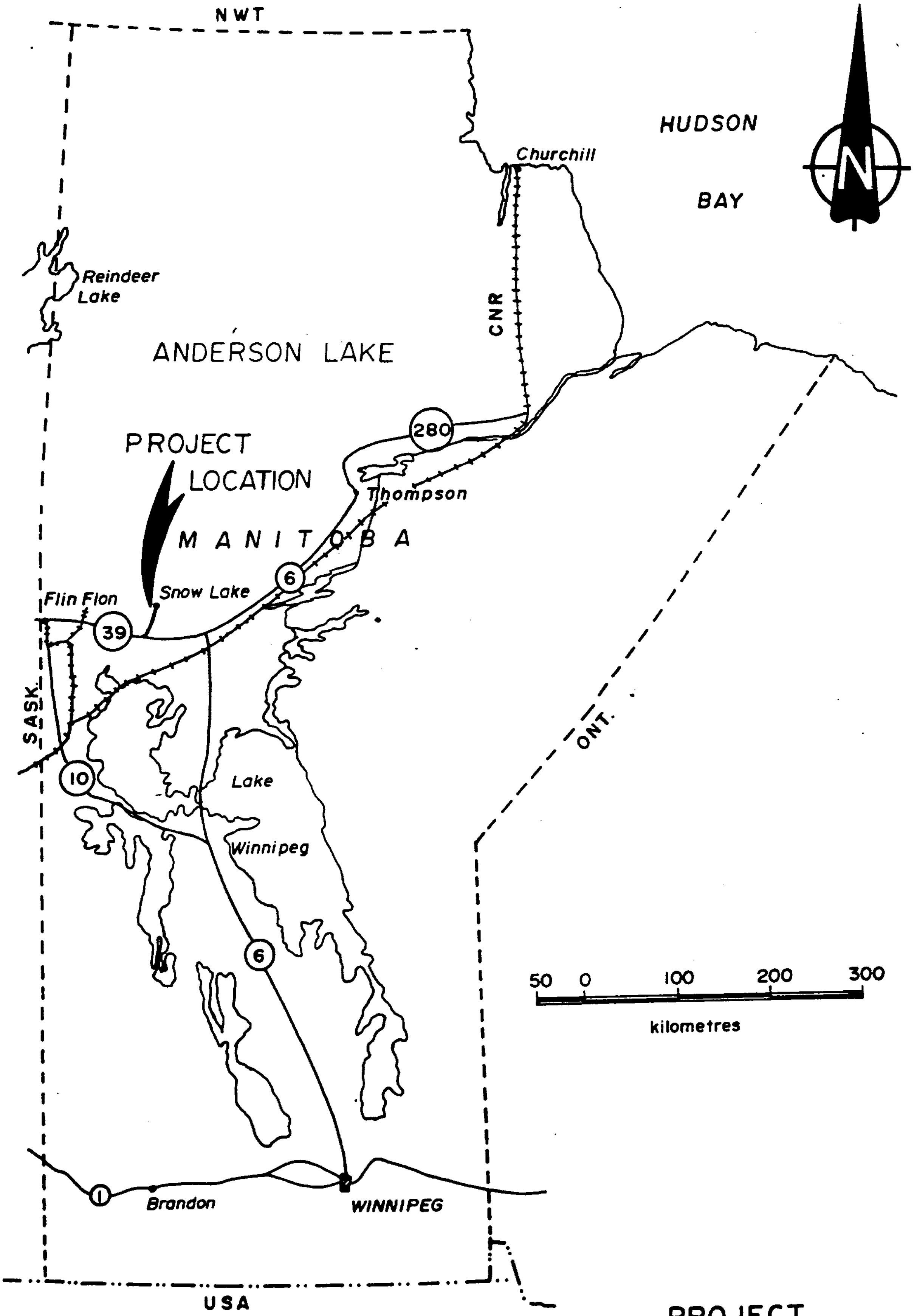
Three cores were collected from the lake in June, 1990, at sites selected to be representative of three contrasting depositional facies: AND-1 (Figure 2-2) was raised from the southeastern arm of the lake, which has never received direct tailings discharges; AND-2 was collected from a previously-active discharge area in the southwest arm of the lake; and AND-3 was recovered from the distal fringe of the zone of active accumulation, about 200 m northeast of the end of the floating outfall (Figure 2-2).

Hydrographic measurements were made at four sites (Stations 2, 4, 6 and 8 in Figure 2-2). A single sample was collected from the lake outlet at the toe of the dam at the end of the eastern arm.

2.3 Study Methods

2.3.1 Core Collection and Processing

Cores (8.8 cm in outside diameter) were collected using butyrate tubes and the lightweight stainless-steel catcher- and cutter-free gravity corer described by (Pedersen et al. 1985). All sampling operations were carried out from the pontooned workboat normally used to move the floating pipeline. An electric winch was employed in all coring operations. The workboat provided a very stable platform, and the electric winch



PROJECT LOCATION MAP

Figure 2 - 1

permitted very smooth deployment and recovery of the corer. As a result, cores of exceptional, undisturbed quality were recovered.

Cores were sealed with a full column of supernatant water immediately after removal from the corer, logged, and transported hand-held to minimize disturbance back to a laboratory set up in the unused and very clean HBMS mine cafeteria in Snow Lake. Detailed core logs are listed in Appendix A.

Interstitial water samples were extracted from the cores in the temporary laboratory in Snow Lake. Special techniques were employed to avoid oxidation artifacts during sampling (e.g. Bray et al. 1973), each core was extruded directly into a nitrogen-filled glove bag by gradually jacking up an o-ring-sealed piston inside the barrel. The supernatant water on the top of the core was carefully removed by siphoning prior to the extrusion, with the exception of the lower 10 cm of water which were removed with a syringe once the core was secured in the nitrogen atmosphere. A sample of this core-top water was collected for each core and was subsequently analyzed as "supernatant" water. In each case, processing commenced within two hours of collection of the core. Samples were sequentially sliced from the core, placed into 250 ml N_2-filled centrifuge bottles, sealed, removed from the glove bag, and centrifuged for 20 minutes at approximately 1200 RFC (Relative Centrifugal Force). The bottles were then placed in another N_2-filled glove bag, the supernatant water in each was decanted into a polypropylene syringe barrel, and the water was expressed through Nuclepore 0.45 mm polycarbonate membrane filters into 30 ml sample bottles. Five to 20 ml were typically recovered, the smallest volumes corresponding to the thin sample intervals used near the top of each core. Ultrapure Seastar concentrated HNO_3 was added immediately to the samples in proportion to their volume to bring the pH to 2. All plasticware and filters were rigorously acid-washed in a Class 100 laminar flow bench as follows. Virgin plasticware (except pipette tips) was: 1) wiped outside and rinsed inside with reagent grade chloroform to remove grease and soluble organic residues; 2) soaked at least 1 day in hot (40° C) 20% reagent-grade HNO_3; 3) rinsed twice with distilled, deionized water (DDW); 4) soaked at least 1 day in 0.1% Seastar ultrapure HNO_3; 5) rinsed once in DDW; 6) soaked at least 1 day in O.1% Seastar ultrapure HNO_3; 7) rinsed once in DDW; and 8) dried covered in a drying oven.

In order to obtain high resolution profiles to define diagenetic reactivity in the upper few centimetres of the sediments, 5 mm sample intervals were used for the top two cm of the core, one cm increments were used for the next several cm, and 3 cm-thick slices were selected at intervals below the upper decimetre. Approximately 16 samples were collected from each core.

All samples were returned to U.B.C. for analysis. The sediment samples were frozen and freeze-dried. An aliquot of each was ground in a tungsten carbide disc mill prior to preparation for X-ray fluorescence, CNS, and coulometric analysis. All analytical methods and quality control procedures are described in Appendix B.

2.3.2 Water Sampling and Analysis

Hydrographic sampling was carried out using a PVC Van Dorn bottle equipped with Neoprene o-rings, and a portable, submersible temperature and dissolved oxygen probe. Conductivity and pH were measured on the water samples immediately after recovery. The water quality sample was collected in an acid-washed 1 L Nalgene polypropylene bottle by submerging the bottle by hand into the outlet flow, rinsing several times, and then filling by submergence. The sample were immediately stored on ice and kept cool for return to Vancouver.

The sample was analyzed by Analytical Services Laboratories Ltd. (ASL) of Vancouver, B.C. Parameters determined included pH, specific conductivity, turbidity (NTU), total dissolved solids and total suspended solids, as well as anions and nutrients including alkalinity, sulphate, chloride, reactive silica, total phosphorus, nitrate/nitrite, ammonia and total organic carbon. Standard analytical methods were used (APHA 1985).

Dissolved metals were analyzed by various atomic absorption and emission spectroscopy methods as follows:

> Inductively coupled argon plasma (ICP) emission spectroscopy for higher concentration elements;
>
> Graphite furnace atomic absorption spectroscopy for low concentration elements;
>
> Hydride generation atomic absorption spectroscopy for arsenic; and
>
> Cold vapour atomic absorption spectroscopy for mercury.

3 - Results

3.0 RESULTS

3.1 Water Quality

Water column profiles of dissolved oxygen and temperature are presented in Figures 3-1 and 3-2 and the data are listed in Table 3-1. Oxygen concentrations were moderate (~7-8 mg L^{-1}) in the upper 3 m of the water column everywhere in the lake at the time of sampling. Depletion was observed at depth, and was considerably more severe at Stations 6 and 8 in the eastern arm, well away from the area of the tailings discharge. O_2 concentrations in bottom water at these sites were <2 mg L^{-1}. The depth of the oxycline varied between these two sites, but was equally steep in both cases (Figure 3-1). Significant oxygen depletion was confined to the lower half-metre at Sites 2 and 4. Despite the observed paucity of oxygen at depth in the lake, stratification was only weakly developed at the time of sampling. The entire water column was warm, and the thermocline poorly established (Figure 3-2). Thus, the low oxygen concentrations must reflect a high benthic oxygen demand, rather than be a product of stratification of the water column. A high benthic demand in the eastern arm of the lake is not surprising given the extremely high organic matter content of the natural sediments in that area. However, the noted depletion close to the bottom at Sites 2 and 4, near the tailings discharge point, suggests that the tailings-rich sediments in that area also have a high benthic oxygen demand. Similar oxygen profiles were obtained by Rescan in August 1989 (see Rescan 1990a). It appears therefore that oxygen depletion may be a typical condition for Anderson Lake bottom waters in the summer.

Water quality parameters measured on the outflow sample indicate that there was little difference in the dissolved salts or metals concentrations between the water leaving the lake in June 1990 and shallow water collected from nearby Station 8 in August 1989 (Table 3-2). The lake is characterized by high conductivity, very high hardness, high dissolved solids and high sulphate. As noted by Rescan (1990a), dissolved aluminum, copper, lead and zinc concentrations frequently exceed water quality guidelines at nearly all sites. The chemistry of the culverted and natural inflows into Anderson Lake is highly variable. Sites which drain the mine area are characterized by low pH, high conductivity and dissolved solids, low alkalinity, high sulphate concentrations, higher chloride concentrations, high reactive silicate concentrations and high dissolved metal

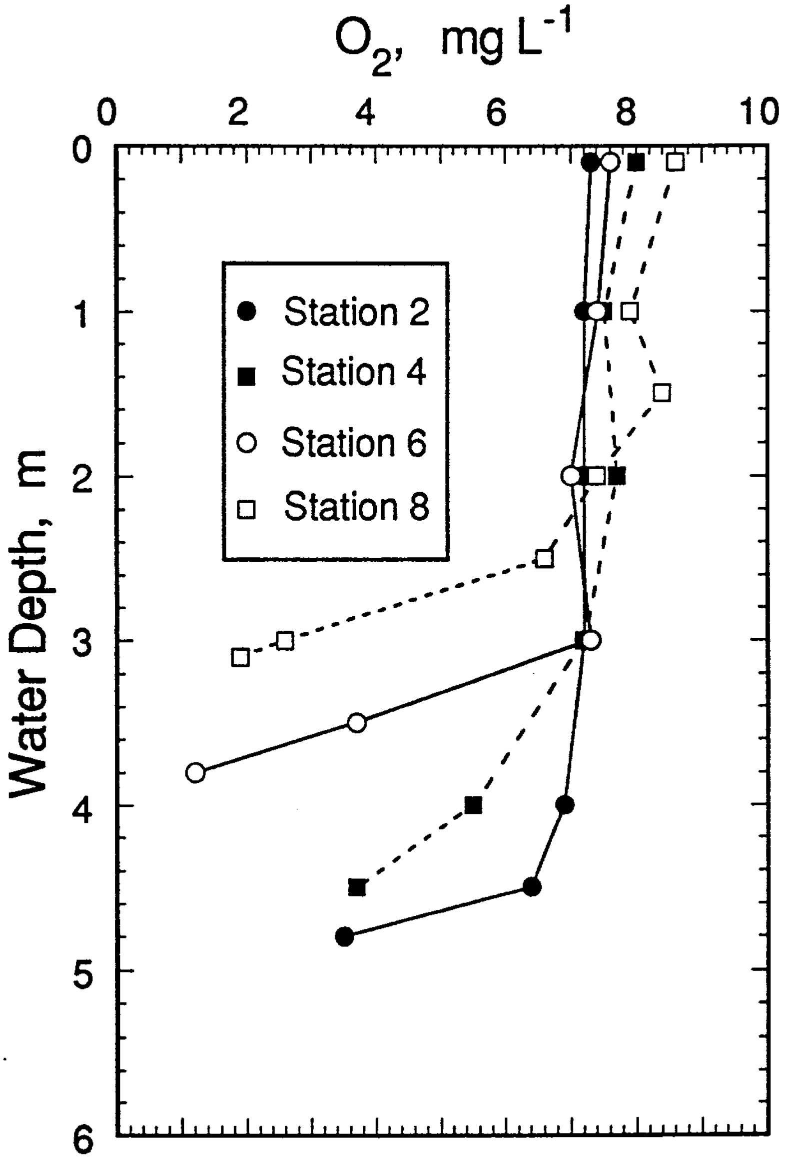


Figure 3-1 Oxygen profiles at four stations in Anderson Lake, June 23 1990, evening.

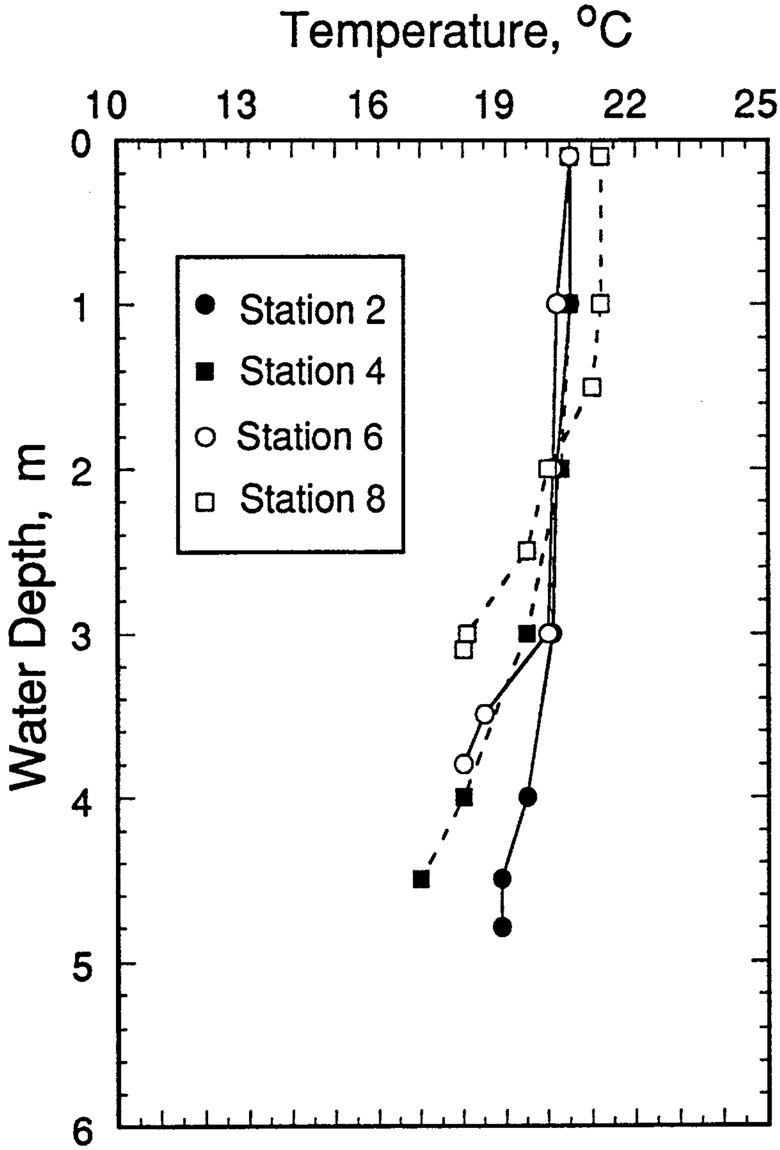


Figure 3-2 Temperature profiles at four stations in Anderson Lake, June 23 1990, evening.

Table 3-1

Hydrographic Data for Four Stations in Anderson Lake, June 23, 1990, Evening

	Depth m	O_2 mg L^{-1}	T deg C	pH	Conductivity µmhos cm^{-1}
STATION 2	0.1	7.3	20.5		1200
	0.5			6.9	
	1.0	7.2	20.5		1200
	1.7			6.9	
	2.0	7.2	20.2		1200
	3.0	7.2	20.1		1200
	4.0	6.9	19.5		-
	4.5	6.4	18.9		-
	4.8 (bottom)	3.5	18.9		-
STATION 4	0.1	8.0	20.5		1150
	0.5			6.9	1150
	1.0	7.5	20.5		1150
	1.7			6.8	1150
	2.0	7.7	20.3		-
	3.0	7.2	19.5		-
	4.0	5.5	18.0		-
	4.5 (bottom)	3.7	17.0		-
STATION 6	0.1	7.6	20.5		1150
	0.5			6.9	
	1.0	7.4	20.2		1150
	1.7			6.8	
	2.0	7.0	20.1		1150
	3.0	7.3	20.0		1150
	3.5	3.7	18.5		-
	3.8 (bottom)	1.2	18.0		-
STATION 8	0.1	8.6	21.2		1150
	0.5			6.9	
	1.0	7.9	21.2		1150
	1.5	8.4	21.0		1150
	1.7				
	2.0	7.4	20.0		1150
	2.5	6.6	19.5		1150
	3.0	2.6	18.1		1150
	3.1 (bottom)	1.9	18.0		-

Table 3-2

Water Quality Data, Anderson Lake Outflow - June 23, 1990

Parameter	Outflow June 23,1990	Station 8 1.5 m depth August 1989
Conductivity (μmhos cm^{-1})	1460	1530
Total Diss. Solids	1400	1360
pH	7.57	6.2
Total Suspended Solids	9.3	8.0
Turbidity (NTU)	3.10	3.2
Alkalinity	5.5	7.51
Chloride	67.1	70.6
Silicate	<1.0	<1
Sulphate	755	774
Ammonia N	0.57	<0.005
NO_3/NO_2 N	0.140	0.44
TOC	6.58	5.8
Ag	0.0004	<0.0001
Al	0.015	0.018
As	0.0005	0.0008
Cd	<0.0002	<0.0002
Cu	0.002	0.002
Fe	<0.030	<0.030
Pb	<0.001	<0.001
Mn	0.160	0.070
Hg	<0.00005	<0.00005
Ni	0.001	<0.001
Zn	0.059	0.020
Ca	304	290
K	14.2	19.0
Mg	17.3	18.1
Na	34.8	37.2

All results expressed in mg L^{-1}, except pH, conductivity, and turbidity. Analyses of a sample collected at Station 8 (1.5 m depth) in August 1989 (Rescan 1990a) are listed for comparison.

concentrations, particularly aluminum, copper, iron, manganese and zinc. The tailings discharge by comparison has a higher pH and alkalinity, higher suspended solids, higher reactive silicates and lower dissolved metal concentrations (Rescan 1990a).

The outflow volume in mid-June was estimated by visually gauging the flow speed (0.5 to 1 m sec^{-1}) and measuring the width (0.5 m) and depth (0.25 m) of the flow through the culvert at the toe of the dam. The calculated outflow is thus roughly 100-200 L sec^{-1}. Given a volume of the lake of 5.7×10^9 L (Rescan 1990a), the flushing or residence time is on the order of 1 to 2 years. Note that there was no outflow in August 1989 as a result of prolonged drought, and that historically, flow only occurrs for 2 to 3 months each year. Therefore, the long-term average residence time of water in the lake may be significantly greater than the crude estimate given above. Because the mine controls the rate of discharge through the outflow culvert, the flushing time of the lake can be manipulated within limits imposed by the natural runoff (or lack thereof). A long residence time has implications for water quality given the significant inputs of dissolved metals to the lake in the tailings slurry and from acid drainage along the shore. In this context, the fact that the zinc concentration in the outflow in June 1990 (~60 μg L^{-1} or 900 nmol L^{-1}) was significantly less than the average concentration of zinc in the water column in August 1989 (130-180 μg L^{-1} or 2000-3000 nmol L^{-1}) may be attributed to dilution by runoff to the lake in the spring of 1990. Note, however, that the lowest zinc and copper values in the water column in August 1989 were measured at Station 8 near the outflow dam. This portion of the lake is subject to the greatest input of uncontaminated runoff from a nearby creek (see Figure 2-2 and the data from sample I3 in Rescan (1990a, p. C-2), which potentially could explain the 1989 observations. It is not clear, however, why dissolved sulphate and chloride levels measured at the same time were as high at Station 8 as elsewhere in the lake. We speculate that another (but unknown) process may be selectively removing metals from the water column in the southeast corner of Anderson Lake. Thus, metal levels measured in the outflow may not be representative of the standing concentrations of metals in the majority of Anderson Lake water away from the southeast corner.

3.2 Solid-phase Chemistry of Cores

The concentrations of major (Fe, Ti, Ca, K, Si, Al, Mg, P and Na) and minor elements (Zn, Pb, Cu, Ni, Co, Mn, Ba, Cr, V, Sr and Rb) were determined by X-ray fluorescence spectrometry as described in Appendix B. Results are listed in Appendix C.

Of the three cores, AND-1 consists of essentially tailings-free, exceptionally organic-rich sediments below about 15 cm depth, as shown by the Zn, Cu and Pb profiles (Figure 3-3) and the organic carbon and nitrogen distributions (Figure 3-4). Organic carbon concentrations range up to 28% in the lower portion of the core, indicating an organic matter content on the order of 60 wt. %. The upper stratum in the core is comprised of a mixture of tailings and natural sediments, and is punctuated by a band between 2 and 4 cm depth which contains extraordinarily high metal concentrations, reaching up to ~12 wt. % Zn (~2 mol kg^{-1} dry wt.) and ~2 wt. % Cu, and about 15 wt. % sulphur (Figure 3-5), equivalent to about 5 mol kg^{-1} dry wt. Despite the considerable distance of this site from the tailings outfall, we attribute both the sulphur and the very high metal concentrations in the 2-4 cm depth interval in Core AND-1 to the presence of very fine-silt-sized tailings; these are characterized visually as a very fine-grained dark-grey band (see Appendix A: Core Descriptions). In addition to the high metal levels, the presence of tailings is supported by mass balance considerations. Assuming that an Fe/Al wt. ratio of 0.6 is representative of natural sediments (such as those at the base of both AND-3 and AND-1), then the 2-4 cm depth interval in AND-1 contains roughly 9 wt. % "excess" Fe, or 1.6 mol kg^{-1} dry wt. If this is hosted entirely by pyrite (FeS_2), about 3 mol kg^{-1} of sulphur occurs in this phase in the 2-4 cm interval. Thus the measured sulphur inventory of 5 mol kg^{-1} at 3 cm depth can be accounted for by the presence of 3 mol kg^{-1} of pyrite and 2 mol kg^{-1} of sphalerite (ZnS), the latter being consistent with the measured Zn concentration.

The tailings in AND-1 are also relatively enriched with cobalt but not Ni (Figure 3-6); Co concentrations reach a maximum of about 250 μg g^{-1} at 2.5 cm depth. Note that major element data are available for only three samples in this core because the very high organic matter content precluded synthesis of fused glass discs for XRF measurement of all the other samples. Several attempts to make such discs failed because the sediments contained insufficient silica to allow formation of a glass; the discs shattered repeatedly during cooling.

Core AND-2 consists of relatively pure tailings with metal concentrations ranging up to 1.2 wt. % Zn, 0.2 wt. % Cu, 700 μg g^{-1} Pb, and a maximum of ~500 μg g^{-1} Co (Figures 3-3 and 3-6). Sulphur concentrations are extremely high, exceeding 20 wt. % in much of the upper two decimetres, and are closely paralleled by the Fe/Al ratio profile (Figure 3-5), indicating that pyrite comprises a very large proportion of the tailings deposited at this location. Admixture of organic matter is minor below about 4 cm

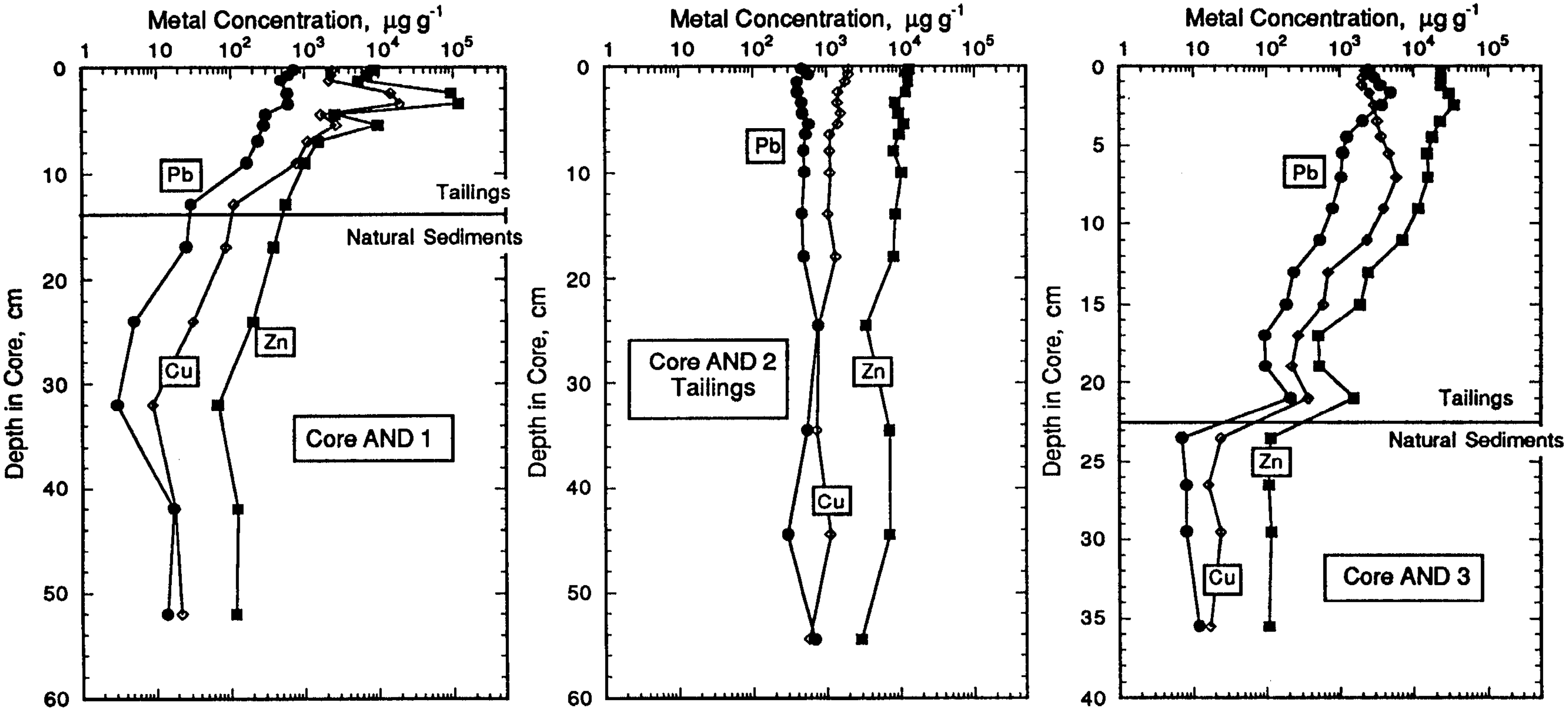


Figure 3-3 Zinc, copper and lead distributions in the sediments of three Anderson Lake cores. Note the log scale on the abscissae.

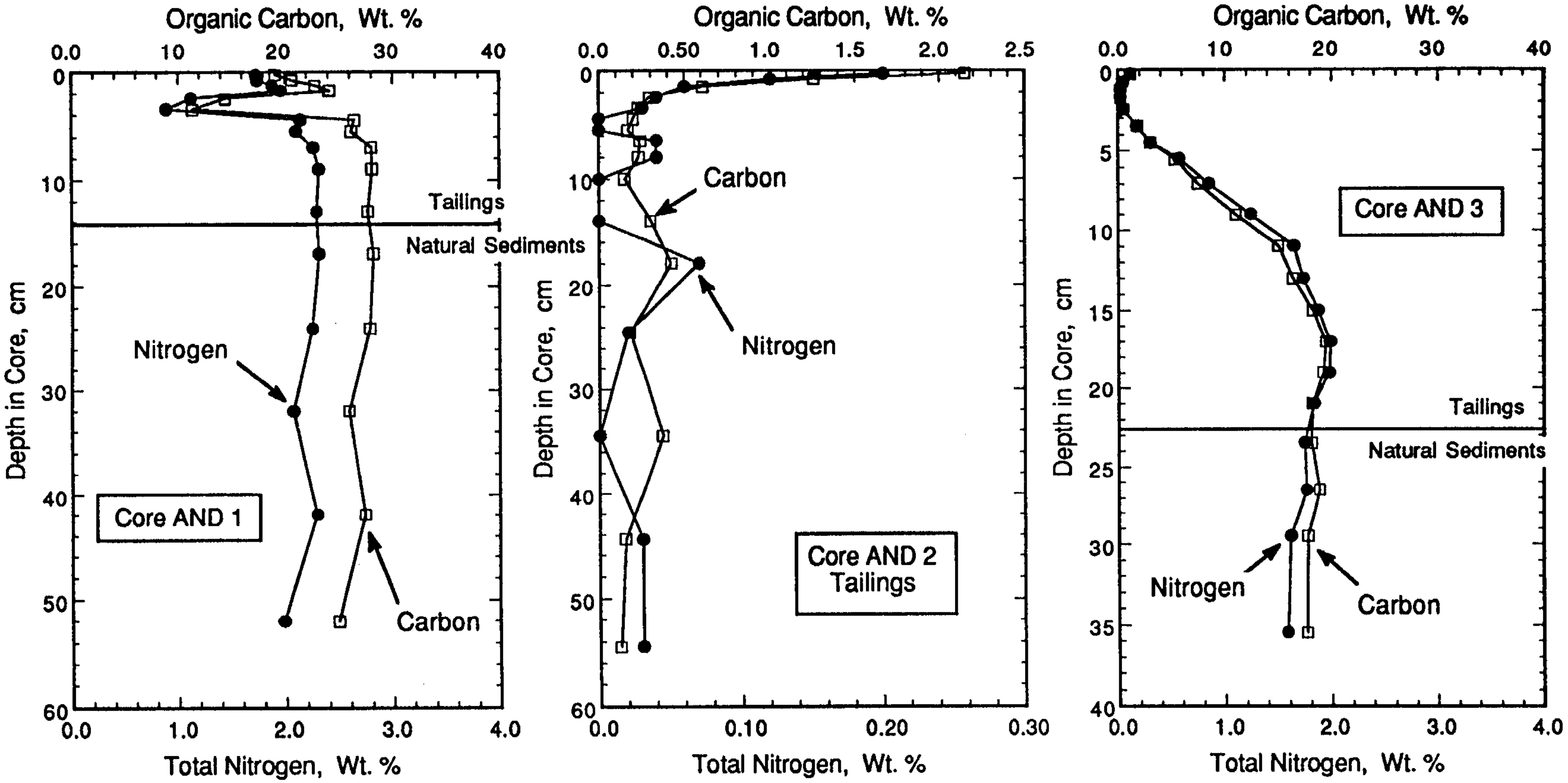


Figure 3-4 Organic carbon and nitrogen distributions in the sediments of three Anderson Lake cores. Note the variable scales on the abscissae.

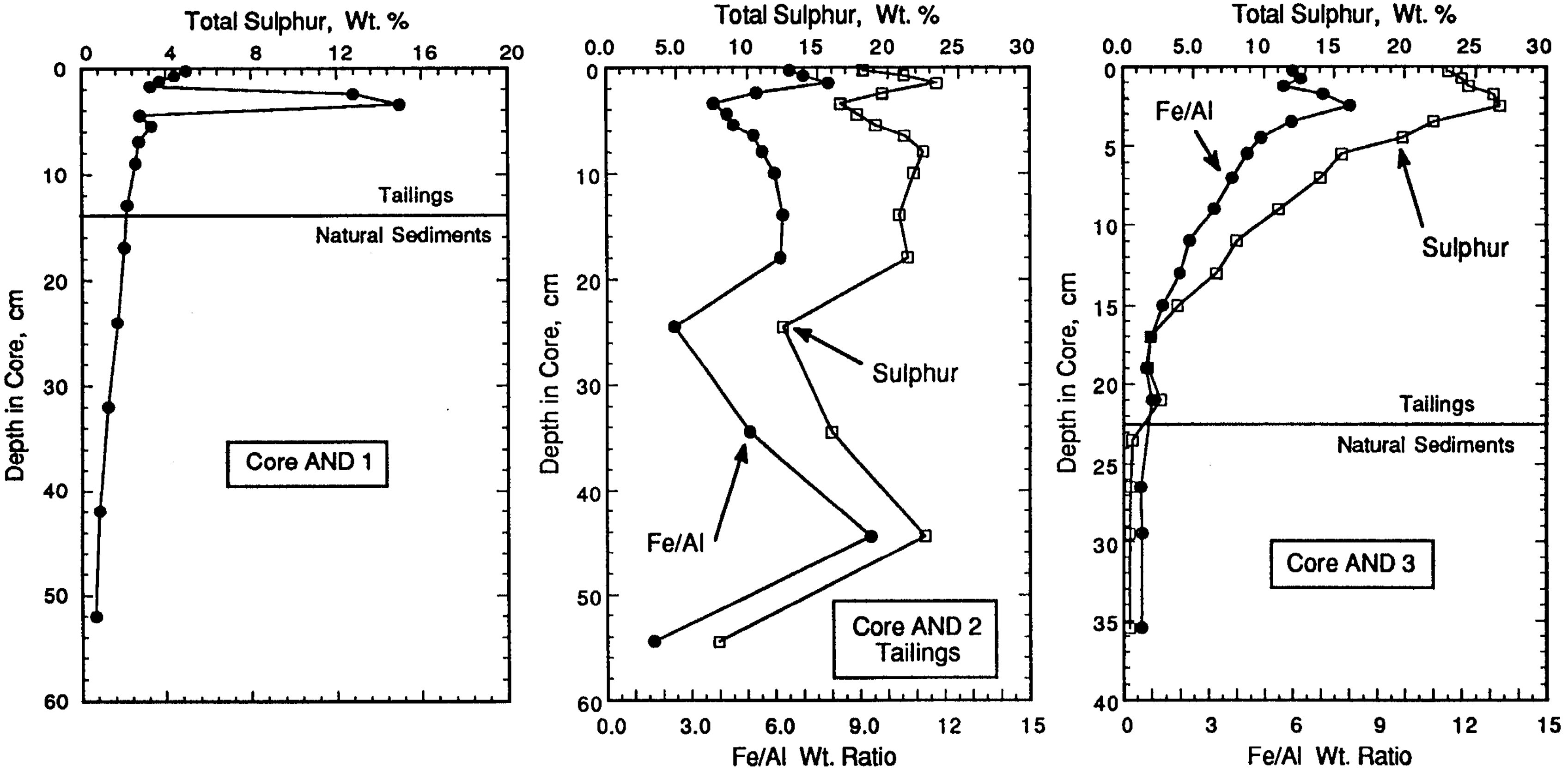


Figure 3-5 Sulphur and Fe/Al ratio distributions in the sediments of three Anderson Lake cores. Note the variable scales on the abscissae.

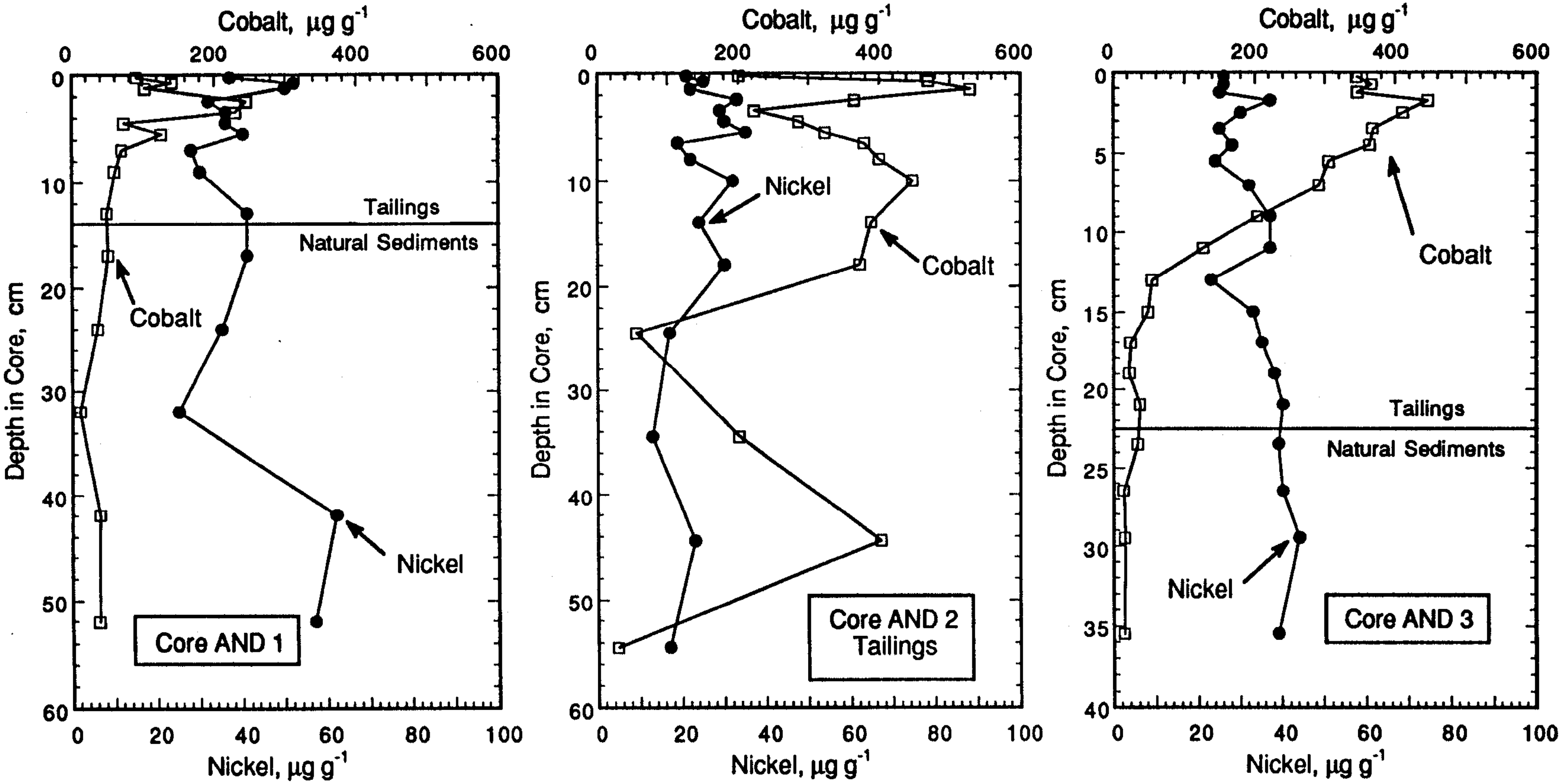


Figure 3-6 Cobalt and nickel distributions in the sediments of three Anderson Lake cores.

depth in the core, but the near-surface sediments are significantly enriched; organic carbon concentrations exceed 2% in the top 5 mm (Figure 3-4). This distribution reflects the resumption of natural sedimentation at this location following relocation of the discharge pipeline in the relatively recent past.

Solid-phase Zn, Cu, Pb and Co profiles indicate clearly that tailings are confined to the upper 23 cm at Site AND-3 (Figure 3-3). The underlying natural deposits are extremely organic-rich, with organic carbon contents ranging to ~20 wt. % (Figure 3-4). Significant amounts of organic material are admixed with tailings in the 5 to 20 cm depth interval, which can be considered to be a transition zone between the pre-discharge natural sediments and the overlying recently-deposited pyritic material. Pyrite is abundant in the upper 5 cm where sulphur contents exceed 25 wt. % and the Fe/Al ratio reaches values as high as 15 (Figure 3-5). The organic content of the surface sediments at this location is relatively low; carbon concentrations are on the order of 0.2 to 1 wt. % in the top four samples (upper 20 mm; Appendix C).

Manganese is not clearly enriched in surface sediments at Site AND-1 (Figure 3-7), where the depositional conditions most closely approximate natural sedimentation among the three sites sampled. Indeed, concentrations in the top centimetre are about 500 $\mu g\ g^{-1}$, which is typical of the natural background, as seen at depth in the same core. The paucity of "excess" Mn at the surface suggests that the oxidation potential in the upper 5 mm is too low to permit Mn oxyhydroxides to precipitate. This suggestion is consistent with the dissolved Mn and Fe profiles discussed in Section 3.3 (below). Similar near-surface Mn distributions are seen at the other two core sites, and the same redox considerations apply. The tailings at depth at all locations are variably enriched in Mn; levels reach ~2000 $\mu g\ g^{-1}$ at mid-depth in Core AND-2 (Figure 3-7) and up to 900 $\mu g\ g^{-1}$ in the top decimetre of Core AND-3. The sulphur and metal-rich horizon between 2 and 4 cm in Core AND-1 similarly contains up to ~900 $\mu g\ g^{-1}$ Mn. The slight enrichment seen at the very top of AND-2 is attributed to a small compositional variation in the tailings and not to precipitation or deposition of an oxide phase in the upper 5 mm. This is supported by the distribution of Mn in pore water, described below.

At all locations, and in all samples where the C_{org} content exceeds about 1 wt. %, the C:N wt. ratio ranges between ~9 and 13 (Figure 3-8). Note that the ratio data are considered to be unreliable where measured % N values were <0.06 %, which is approaching the detection limit of the CHN analyzer. These data are shown as open

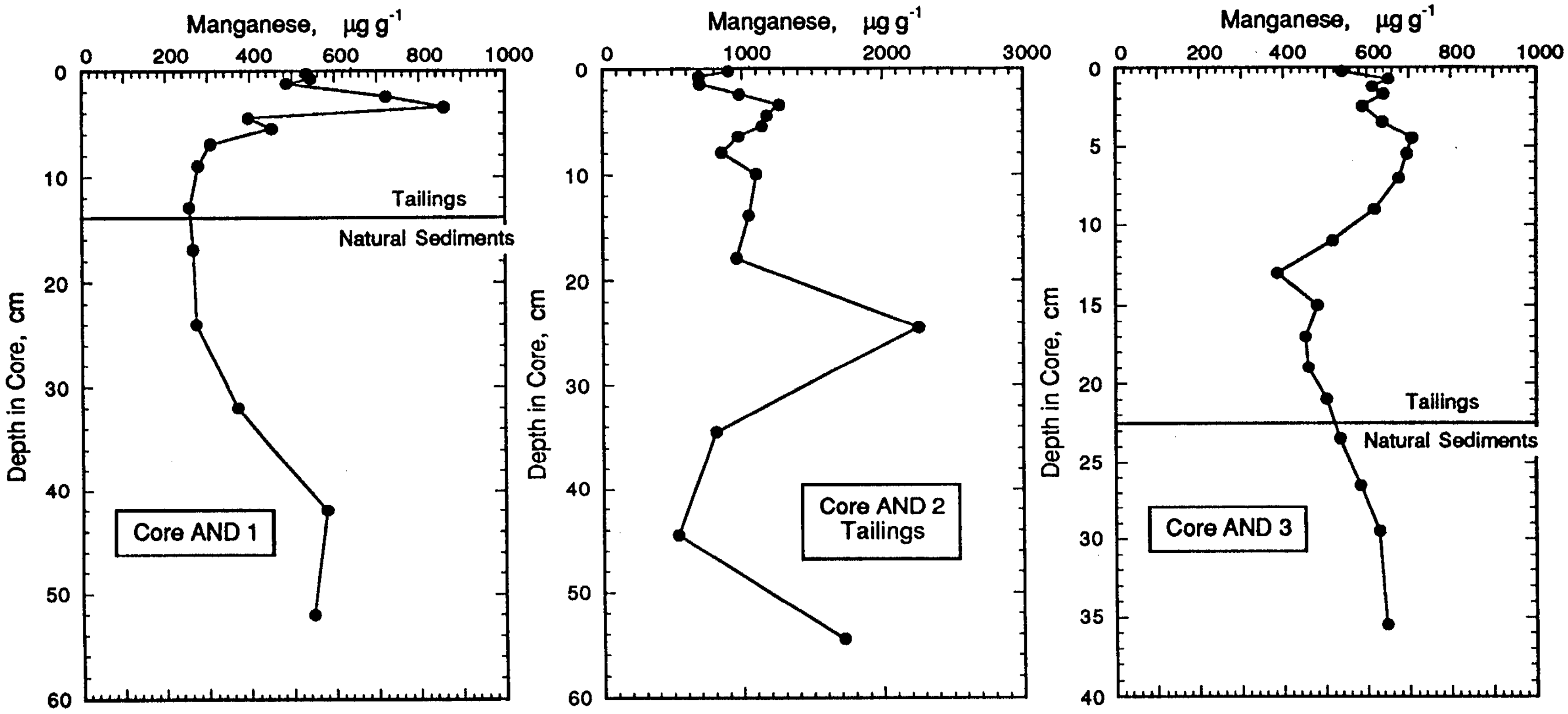


Figure 3-7 Manganese distributions in the sediments of three Anderson Lake cores. Note the variable scales on the abscissae.

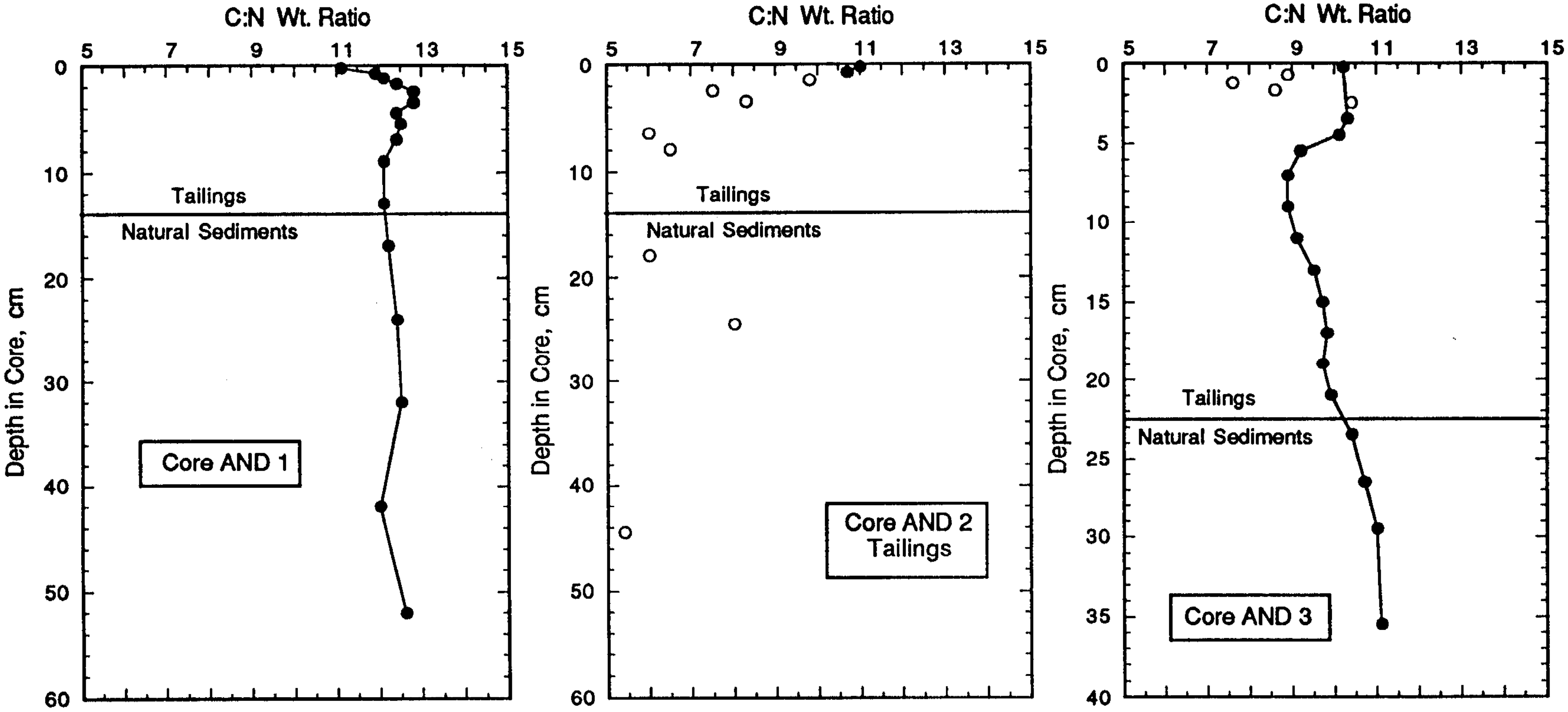


Figure 3-8 C:N ratio distributions in the sediments of three Anderson Lake cores.

circles in Figure 3-8. There is little evidence of systematic variation with time at the two sites (AND-1 and AND-3) where good ratio data are available, with the exception of the upper few centimetres at AND-1 where the ratio decreases slightly toward the surface (Figure 3-8). A slight contrast exists between the mean ratios of the natural deposits at AND-1 (~12.2) and AND-3 (~11). This may reflect a small difference in the composition of the organic matter which accumulated at these two locations in the past.

Major element distributions (as a ratio to Al in Figures 3-9 to 3-11, to illustrate compositional variations rather than dilution effects by such variably dominant phases as pyrite) demonstrate that the tailings are composed of different aluminosilicate minerals than the natural fluvial detritus deposited in the lake. High Si/Al and Mg/Al ratios and low K/Al ratios in the tailings are particularly distinct when compared to the natural sediments in the lowermost strata of Core AND-3. X-ray diffractograms and petrographic studies (Rescan 1990a) indicate that quartz, albite feldspar, chlorite and muscovite are common in the tailings, while calcite occurs in minor amounts (see Table C-3). Pyrite is particularly abundant in the tailings as indicated by the Fe/Al ratio distribution discussed above. The high Si/Al and Mg/Al ratios characteristic of the tailings reflect the abundance of quartz and chlorite in these deposits. Similarly, the low K/Al ratio in the tails suggests that muscovite and possibly orthoclase feldspar are proportionately more common in the natural detritus. Relatively low Ti contents in the tailings (Figure 3-9) indicate that such principal host minerals for titanium as ilmenite and titanomagnetite are more abundant in the natural sediments.

3.3 Interstitial Water

Filtered pore waters were analyzed for dissolved Zn, Cu, Pb, Fe and Mn as described in Appendix B. All concentration data are listed in Appendix D. Some samples were believed to be contaminated and are shown as open circles in the figures presenting the concentration profiles, and are denoted with an asterisk in Appendix D. It appears likely that the presumed contamination resulted from the addition of very small amounts of tailings to the pore water samples after or during filtering; the addition of acid then dissolves the sulphide particles yielding high metal concentrations. In such cases (e.g. the 0.5-1.0 cm sample in AND-3 (see Appendix D)) all the metal levels are enriched. Slight contamination specific to one or two metals is also suspected in some cases (e.g., at 0.75 and 1.25 cm depth for Pb in AND-1). The criterion used to define such suspected disturbance of the samples is an obvious lack of consistency of high

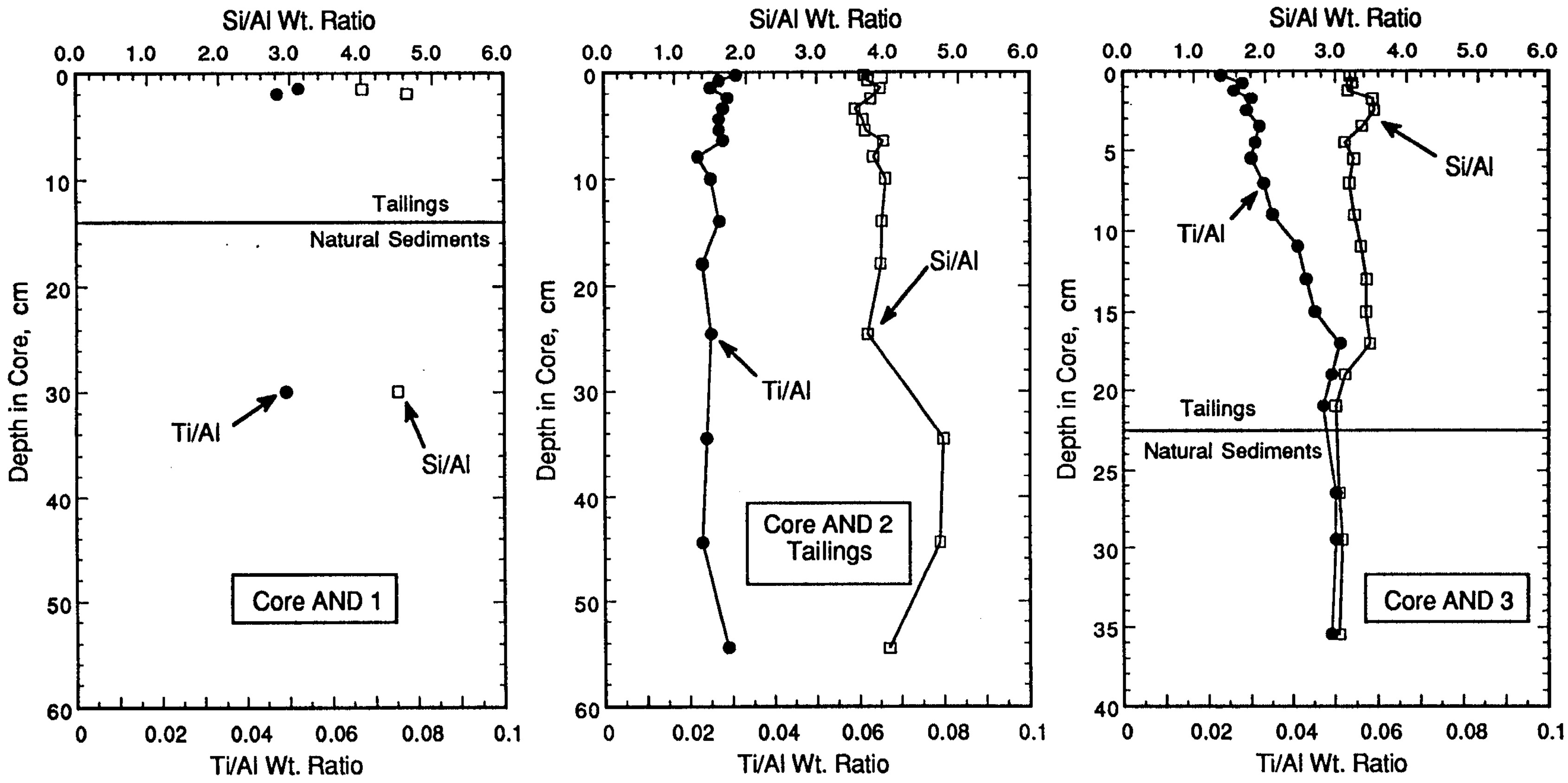


Figure 3-9 Si/Al and Ti/Al distributions in the sediments of three Anderson Lake cores.

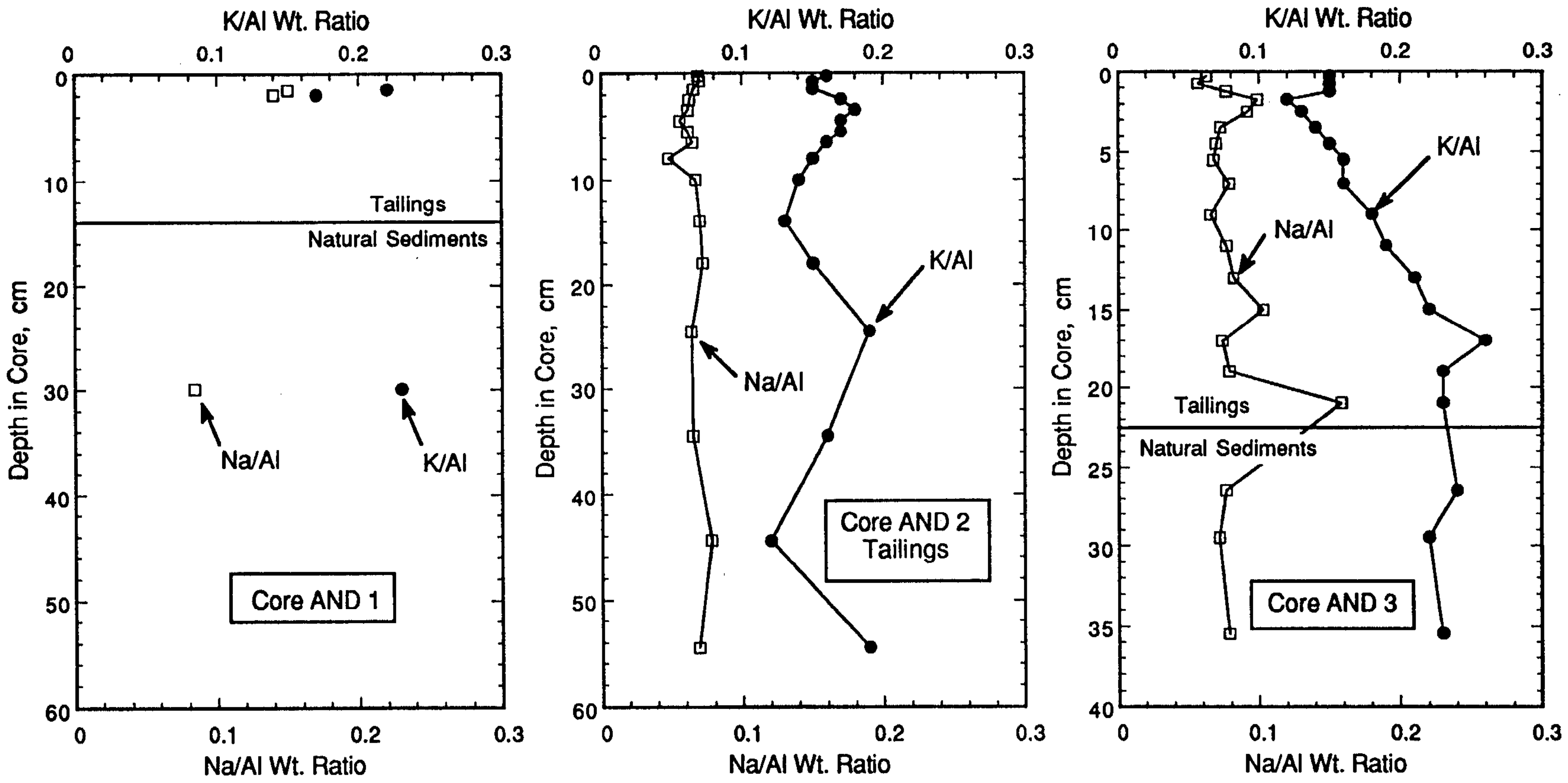


Figure 3-10 K/Al and Na/Al distributions in the sediments of three Anderson Lake cores.

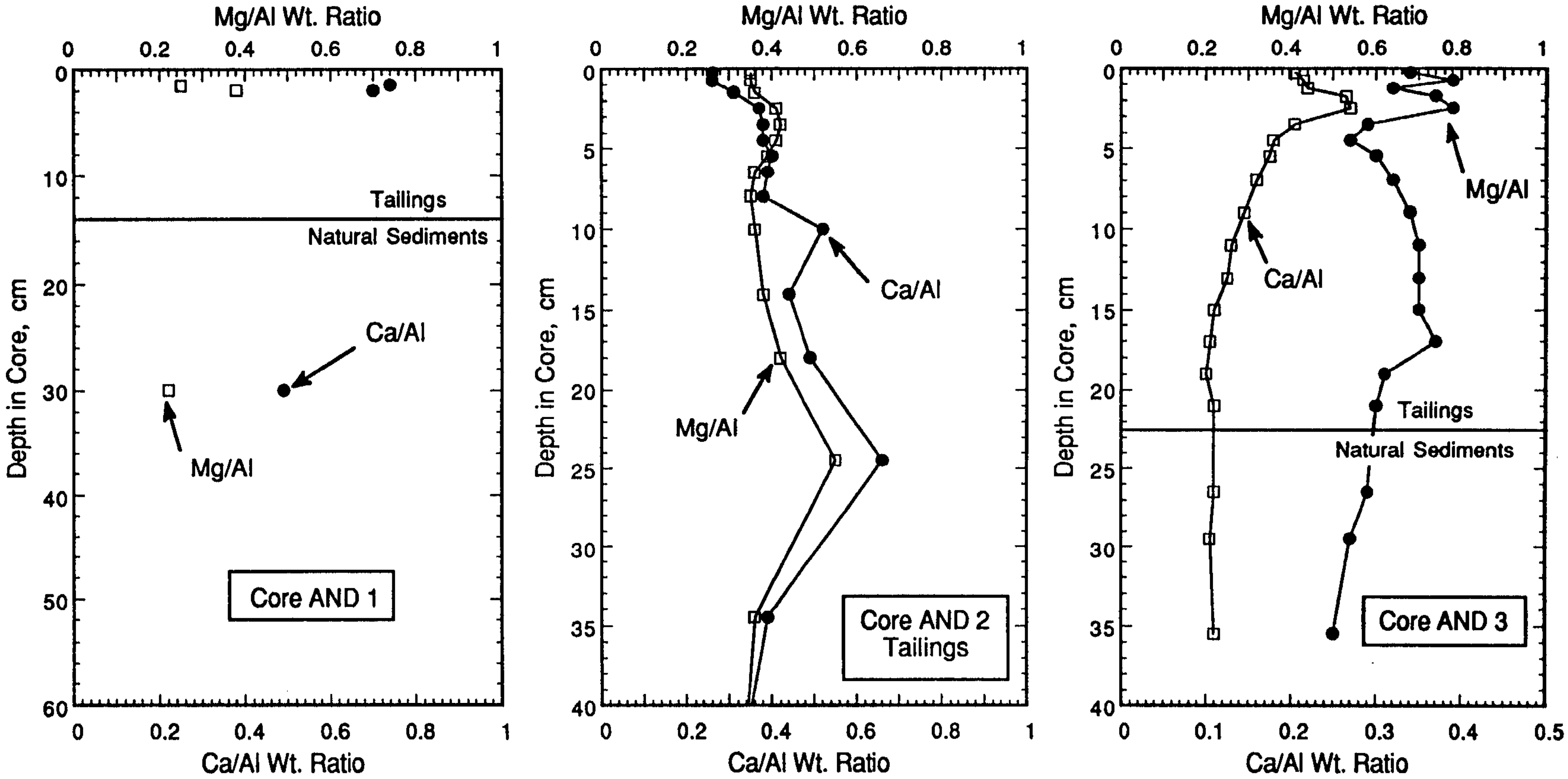


Figure 3-11 Mg/Al and Ca/Al distributions in the sediments of three Anderson Lake cores. Note the variable scales on the abscissae.

concentrations with values measured in adjacent samples. Such "spikes" are rejected from subsequent interpretation of process, but are shown in the profiles for the sake of completeness, and with recognition that contamination is subjectively defined in this report.

Dissolved Fe and Mn profiles are shown in Figures 3-12 and 3-13 respectively. Concentrations of several μmol L^{-1} Fe and ~2.5 μmol L^{-1} Mn were measured in supernatant waters at all sites. The latter are very similar to the dissolved Mn concentrations (typically ~3 to 3.5 μmol L^{-1}) measured throughout the water column in August 1989 (Rescan 1990a). Fe concentrations in August 1989 were less than about 0.6 μmol L^{-1} (Rescan 1990a), significantly lower than the values reported here. In all three cores dissolved iron concentrations reach levels as high as 150 μmol L^{-1} in the near-surface zone and are depleted at depth. Different subsurface distributions are observed for Mn. In AND-1 the dissolved manganese content increases essentially monotonically with depth to a maximum of about 12 μmol L^{-1} in the natural sediments near the base of the core. A similar concentration characterizes the natural deposits in AND-3, but the profile is marked by an approximately invariant concentration over much of the upper 15 cm of tailings, and a sharp decrease toward the surface in the top two cm (Figure 3-13). A lower maximum concentration of ~6 μmol L^{-1} occurs in the upper decimetre of AND-2.

Dissolved Zn values in the supernatant waters at the three sites (Figure 3-14) range between ~1 μmol L^{-1} (at AND-3) and 3 μmol L^{-1} (at AND-1 and 2). These levels are similar to measurements made in the water column in August 1989 (Rescan 1990a) and confirm that the lake is polluted with respect to dissolved Zn. At all three locations, dissolved Zn concentrations decrease sharply with depth to levels of a few to a few tens of nmol L^{-1}, typically within 5 cm of the interface.

Dissolved Cu concentrations in supernatant waters at all three sites are on the order of 50 nmol L^{-1}, considerably less than levels measured in the water column in August 1989 (Figure 3-15). As for Zn, the measured concentrations decrease precipitously with depth in cores AND-2 and AND-3, and more slowly in AND-1. Extremely low or undetectable (i.e. <1 nmol L^{-1}) concentrations characterize the pore waters below about 2 cm depth in the former pair of cores. Such low values are also observed in the lower four decimetres of core AND-1.

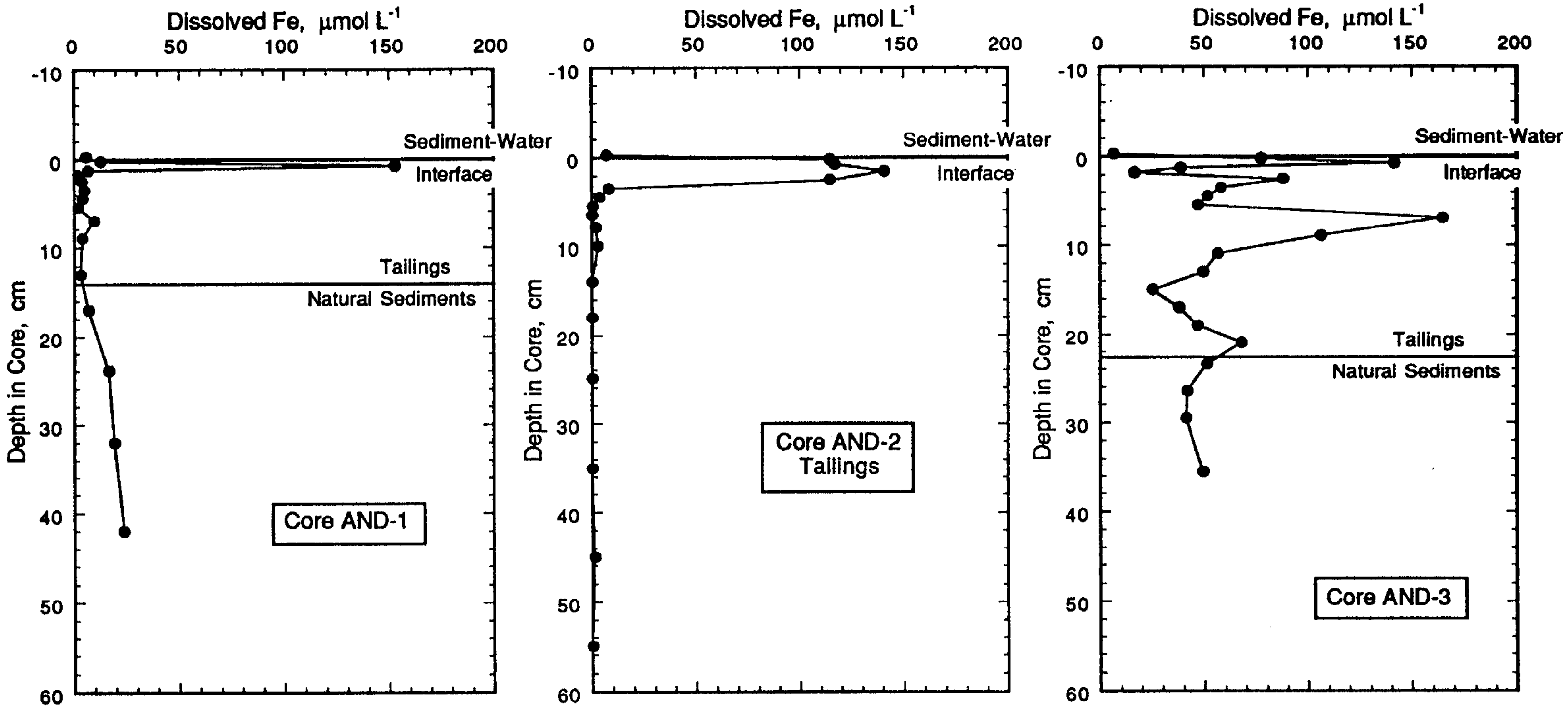


Figure 3-12 Dissolved Fe distributions in the interstitial waters of three Anderson Lake cores.

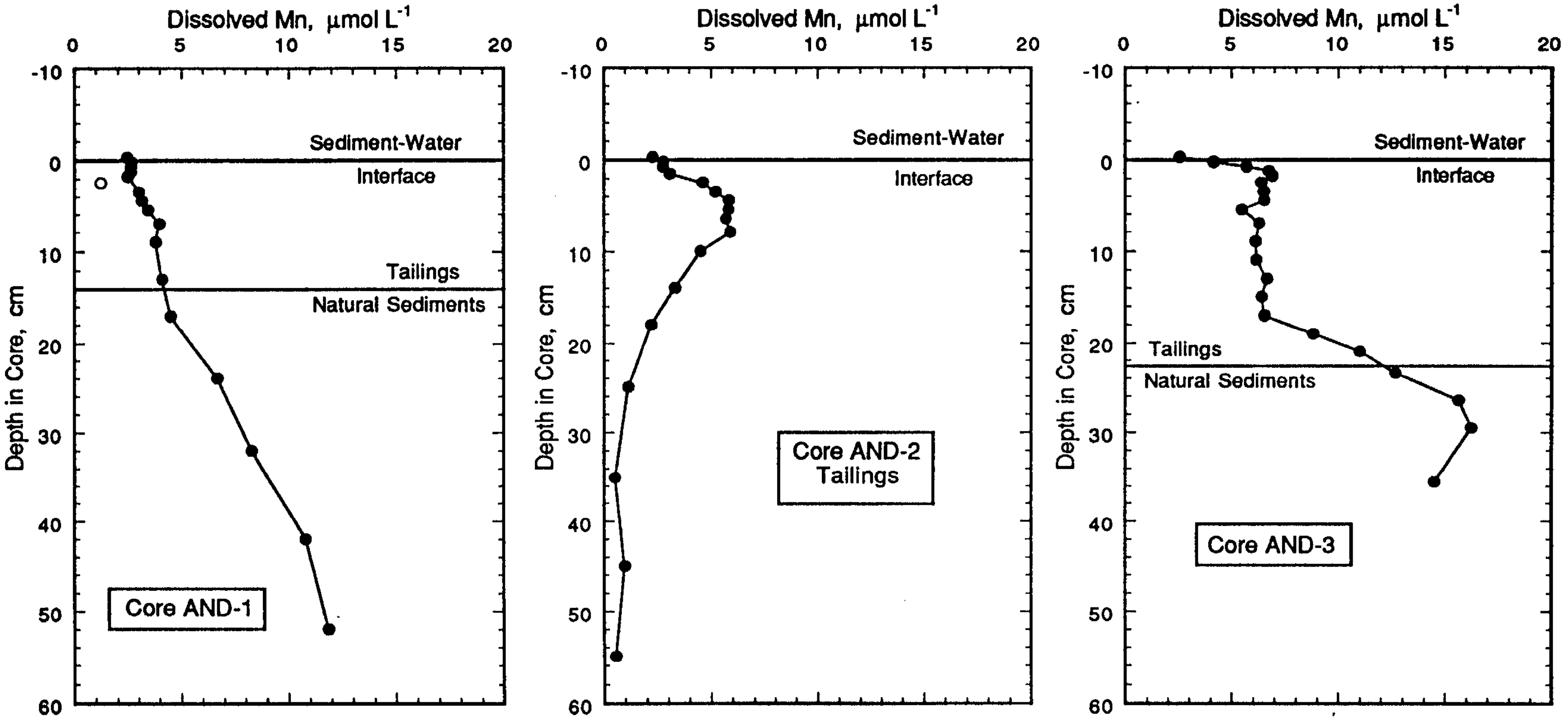


Figure 3-13 Dissolved Mn distributions in the interstitial waters of three Anderson Lake cores.

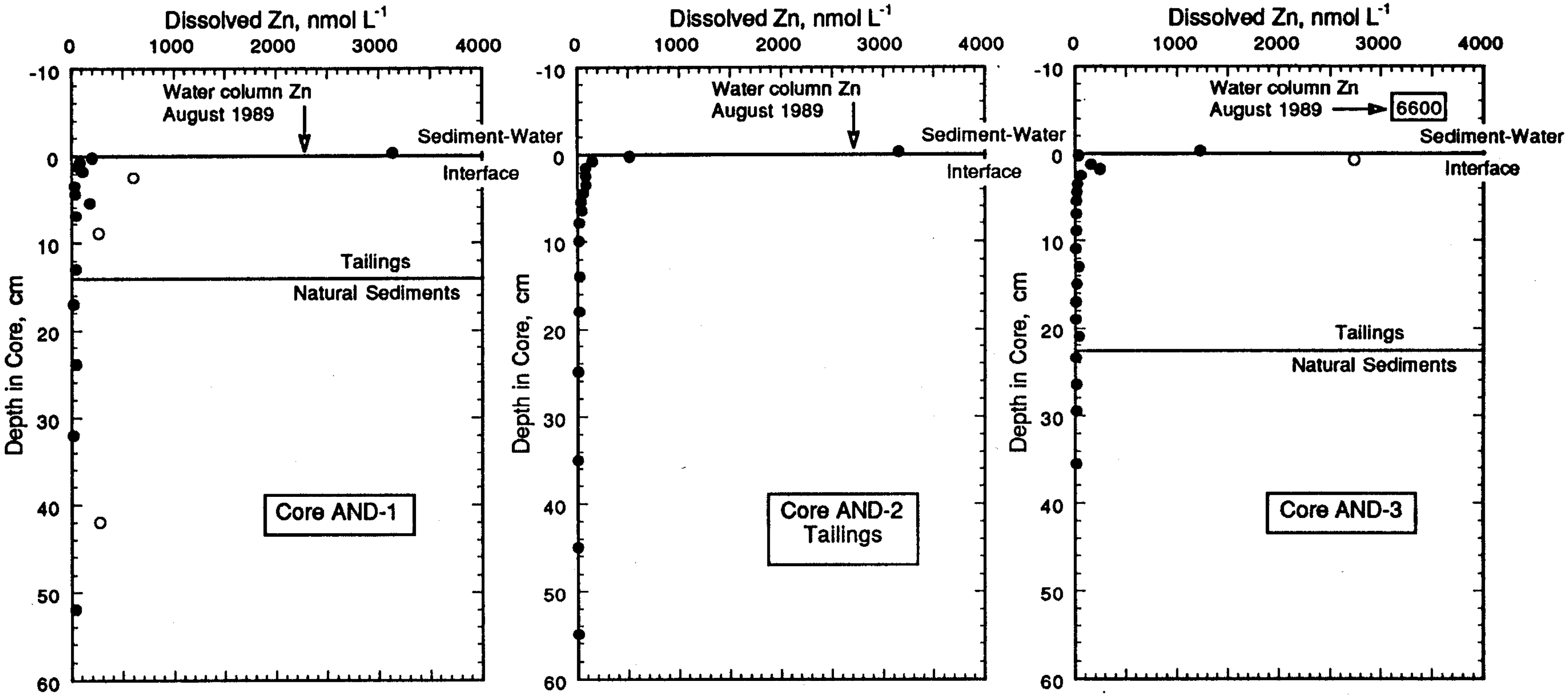


Figure 3-14 Dissolved Zn distributions in the interstitial waters of three Anderson Lake cores. Samples suspected to be contaminated are denoted by open circles.

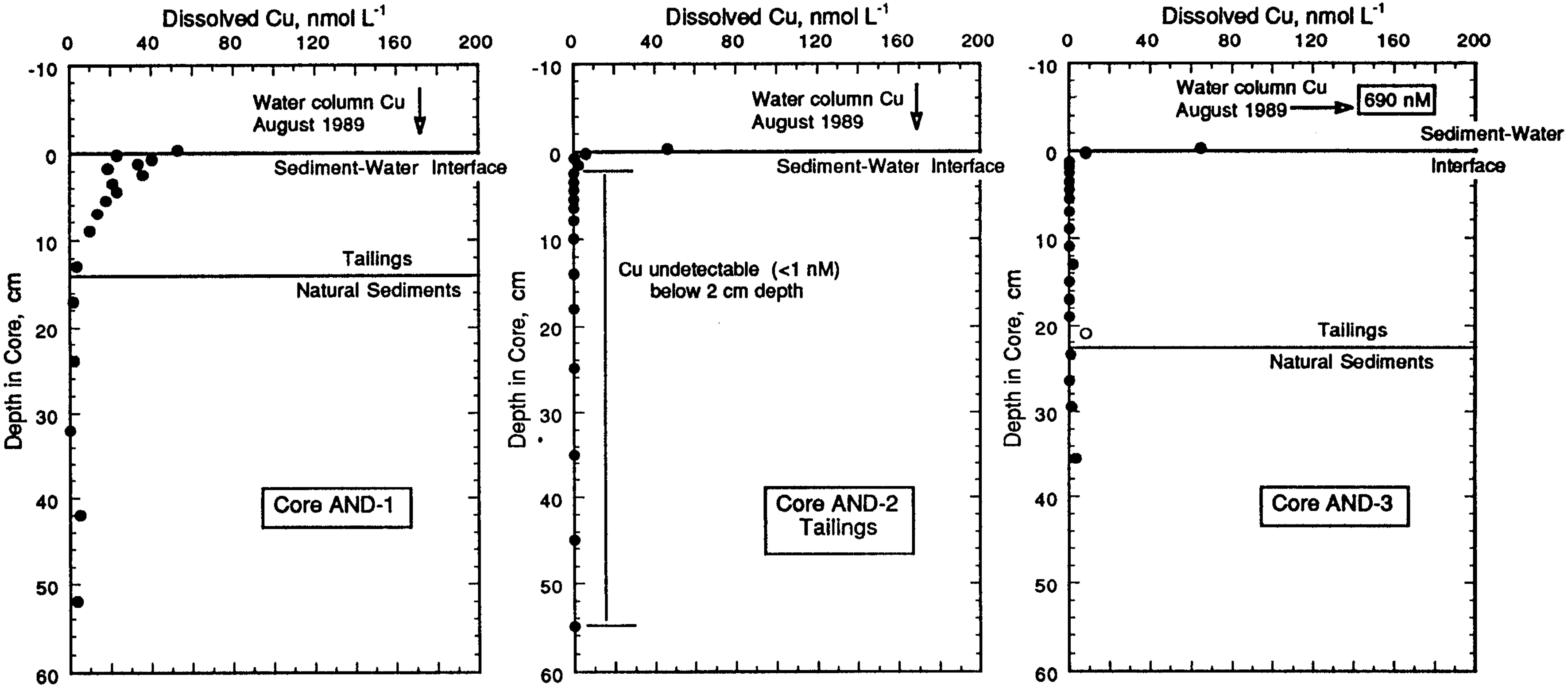


Figure 3-15 Dissolved Cu distributions in the interstitial waters of three Anderson Lake cores. Samples suspected to be contaminated are denoted by open circles.

Pb concentrations in supernatant waters are relatively low (2-5 nmol L^{-1}), and at sites AND-2 and AND-3 are substantially less than levels measured in the water column in August 1989 (Figure 3-16). The subsurface distributions are very similar to those for Cu; a precipitous decline in the top one or two centimetres characterizes the profiles at AND-2 and AND-3, and a more gradual decrease with depth is seen in Core AND-1. At all three sites, concentrations at depth in the cores are near or below detection limit (on the order of 0.1 nmol L^{-1}, Appendix B).

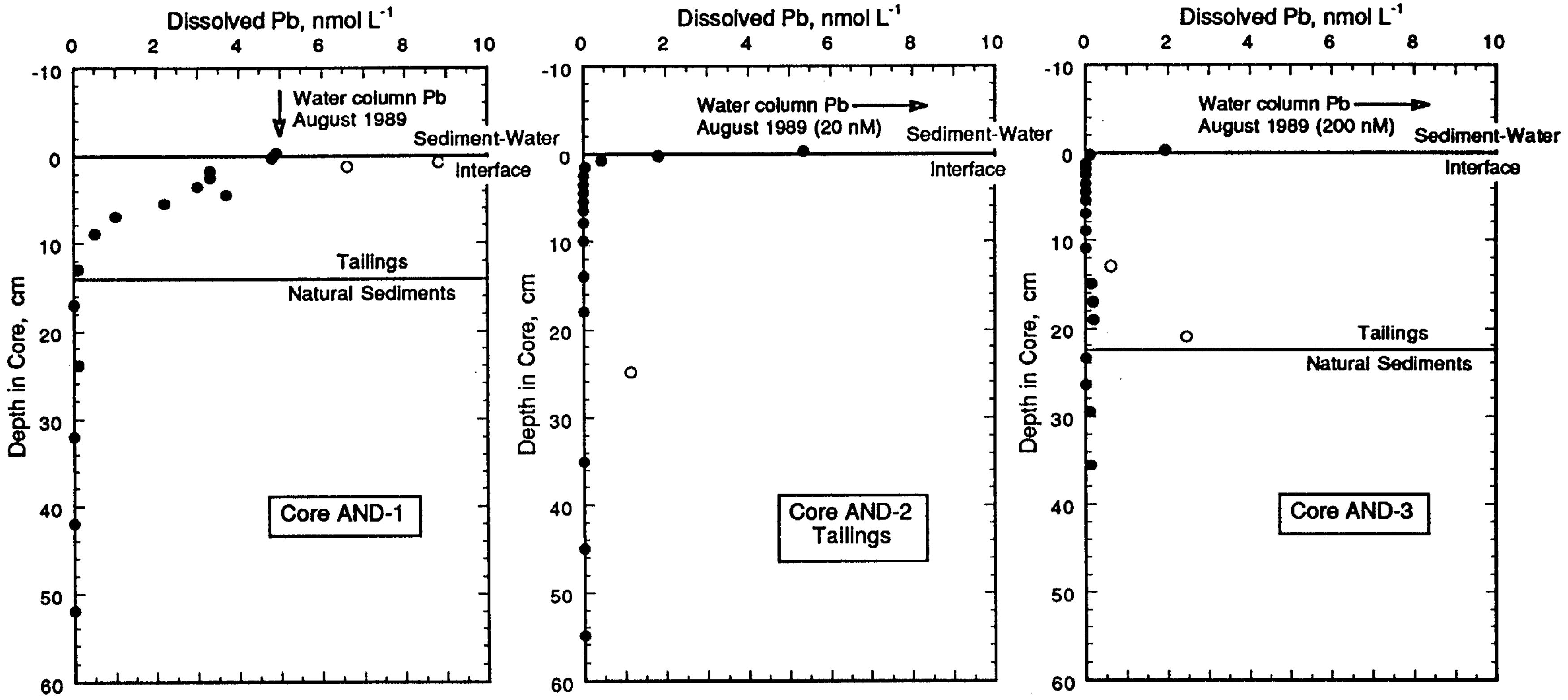


Figure 3-16 Dissolved Pb distributions in the interstitial waters of three Anderson Lake cores. Samples suspected to be contaminated are denoted by open circles.

4 - Discussion

4.0 DISCUSSION

4.1 Manganese and Iron Diagenesis

Bacterial oxidation of reactive organic matter in lacustrine sediments proceeds via a series of overlapping electron-transfer reactions in which the thermodynamically-unstable reduced carbon compounds serve as electron donors and various oxidants act as terminal electron acceptors as degradation proceeds (see review in Chapter 3 of Rescan, 1989). During oxidation, organic matter will donate electrons to orbitals of lowest available energy level as this produces the greatest free energy gain per unit of organic material oxidized. The reaction sequence proceeds in an order mandated by the net free energy yield, with aerobic oxidation (the highest-yield reaction) preceding (in thermodynamic order) denitrification, manganese and iron oxyhydroxide reduction, sulphate reduction, and methanogenesis (Froelich et al. 1979).

In sediments in mesotrophic or eutrophic lakes, the organic carbon content is usually sufficient to establish anoxic conditions at depths ranging from a few millimetres to one decimetre. The resulting chemical zonation is therefore characterized by a decreasing redox potential with depth and the release to interstitial solution of a number of reaction products. Two such products are dissolved manganese and iron. Because Fe oxyhydroxide reduction commences almost as soon as O_2 has been depleted, the depth at which Fe^{2+} first appears in pore water is a reasonably precise indicator of the sub-bottom oxic-anoxic boundary (Rescan 1989). MnO_2 reduction and associated addition of Mn^{2+} to pore water occurs at slightly shallower depths, thus, at a slightly higher oxidizing potential. The presence of Fe and Mn oxide phases in near-surface sediments has important implications for the diagenetic behaviour of heavy metals, given that both oxyhydroxides are effective at scavenging metals from solution (Kadko et al. 1987).

There is no indication in the present study that oxides are enriched in the surface sediments at any of the three sites sampled. However, the background level of iron is very high due to the concentration of pyrite in the sediments, and the presence of a small proportion of oxyhydroxide would be very difficult to detect using bulk sediment analysis. Analytically, it is similarly difficult to define unequivocally the occurrence of a Mn oxide phase at the surface of any of the cores. The fact that concentrations of dissolved Fe and Mn higher than in the overlying supernatant water were measured in the top pore water sample (0-5 mm) at all three sites suggests that the sediments must be anoxic or suboxic at these very shallow depths. The shape of the iron profiles rules out upward diffusion of Fe from a remote source at depth as being responsible for the presence of dissolved Fe^{2+} in the top 5 or 10 mm. Considering that dissolved iron is very susceptible to oxidation to ferric oxyhydroxide (thus, removal from solution) in the presence of molecular oxygen, we conclude that oxygen is essentially depleted at all three locations in the lake within a few millimetres of the interface, and certainly within the top centimetre.

The comparatively high supernatant iron levels may reflect dissolution of iron oxides and remobilization from the surface sediments; certainly, the pore water iron enrichments near the interface (Figure 3-12) must support an upward efflux of the metal to the water column. Because the lake is slightly acidic (the pH measured in the field in August 1989 was on the order of 6 [Rescan 1990a]), and considering that oxygen was partially depleted in near-bottom waters at the time the cores discussed here were collected (Section 3.1), the rate of oxidation of Fe added to the overlying water by a benthic efflux will be relatively slow, and Fe^{2+} will be able to persist in the water column for a longer period than if the lake were more alkaline. Presumably these conditions could account for the observed concentrations of Fe in the supernatant waters, although the addition of dissolved Fe to the acid lake water from surface runoff and the tailings discharge may also contribute to the standing dissolved iron inventory.

The pore water Mn concentrations measured in the natural deposits in cores AND-1 and AND-3 are much lower than observed in comparative facies elsewhere, particularly natural sediments in Buttle Lake, B.C., where Mn levels generally exceed 100 μmol L^{-1} at depths on the order of one or two decimetres (Rescan 1990c). This suggests that the proportionate input of Mn oxide phases to the sediments in Anderson Lake is relatively low, and/or that the suboxic nature of the near-surface deposits inhibits burial of oxyhydroxides, thereby reducing the potential for dissolution at greater depths. Another parameter appears to be important at Site AND-1. The shape of the Mn^{2+} profile indicates that a source below the base of the core is supplying upward-diffusing manganese to the upper five decimetres of the sediment column. A similar phenomenon was observed at two sites in Buttle Lake. Presumably, this reflects an historical change in the composition of sediments deposited at Site AND-1, but the nature and date of such an event is unknown. In any event, this phenomenon has no influence on the distribution or behaviour of dissolved Zn, Pb or Cu, as noted below. There is no indication of a similar deep source of Mn^{2+} at Site AND-3. Given the recently-commenced deposition of tailings at this location, diffusive steady-state cannot be assumed. Thus, the apparent concave-up shape of the profile between 10 and 30 cm depth in the core cannot be ascribed to consumption of upward-diffusing Mn by the tailings; instead it may reflect the recent, sudden change in deposition at that location. Given a bulk diffusion coefficient (corrected for porosity and tortuosity) for Mn^{2+} at 6 °C of $\sim 3.5 \times 10^{-6}$ cm^2 sec^{-1} (calculated from the data in (Li and Gregory 1974)), it would take at least 2.5 years for Mn^{2+} to diffuse 15 cm (from the maximum at ~30 cm depth to a precipitation site at 15 cm); this is of the same order or longer than the length of time since the depositional regime markedly and suddenly changed at Site AND-3. Therefore, it is not reasonable to expect that diffusion could have smoothed the pore water profiles and reestablished diagenetic equilibrium for manganese between the solid-phase and the pore water. The dissolved Mn profile at AND-2 similarly may not reflect diffusive steady-state, in that the tailings at that site were deposited relatively recently and at a rapid rate. Note that the same rationale does not apply to iron and the other metals since these are much more reactive than Mn with respect to sulphide, and both production and consumption reactions for these elements are occurring within a few to several centimetres of the interface. Under such conditions, diffusion can smooth the pore water profiles with respect to reactions with the solid phase on time scales on the order of several weeks to a year.

4.2 Zinc, Copper and Lead Diagenesis

It is clear that from the analyses made in August 1989 (Rescan 1990a) that the Anderson Lake water column is contaminated with respect to Zn, Cu and Pb. High concentrations of all three metals were measured in the supernatant water of each of the trio of cores collected in June 1990, confirming the 1989 water column data. At all sites, the dissolved Zn, Cu and Pb concentrations decrease abruptly with sub-bottom depth, indicating that both the natural sediments and tailings are actively removing metals from solution. This observation is independent of sedimentation rate, which must be much lower at Site AND-1 than at the other two tailings-replete locations. This fact, along with the recognition that diffusion over length scales of a few centimetres would quickly smooth any chemical manifestations in pore water of an abrupt change in depositional or redox conditions, rules out non-steady-state effects as being responsible for the dissolved metal depletions at shallow depths in the cores. Thus, the tailings and natural sediments near the interface must be in diagenetic equilibrium with their associated interstitial waters.

As noted above, the dissolved Fe profiles indicate that the sediments are anoxic at extremely shallow depths. Sulphate reduction should therefore be occurring with concomitant production of H_2S within a short distance below the interface. Indeed, framboidal pyrite is a common trace constituent in near-surface sediments collected at a number of location in the lake (Rescan 1990a). The presence of this authigenic phase is consistent with the indicated consumption of dissolved iron.

Sulphate is abundant in Anderson Lake water (Rescan 1990a); concentrations in 1989 were typically 8 mmol L^{-1} throughout the water column. Two sources for the ion are apparent: a) acid runoff emanating from the road along the north margin of the lake, which was built of tailings some time ago, contains about 16 mmol L^{-1} of SO_4^{2-} (Rescan 1990a); and b) the tailings slurry discharged at the surface from the floating pipeline contains ~6 mmol L^{-1}. Note that both sources are of relatively recent origin. The historical sulphate content of the lake water was probably quite low. This suggestion can explain the dissolved iron enrichments in pore water observed at depth in the natural sediment facies in AND-1 and AND-3. We speculate that prior to the addition of mining-related sulphate to the lake, the quantity of SO_4^{2-} available to produce sulphide via sulphate reduction was insufficient to precipitate all the dissolved Fe^{2+} released to pore water from oxide dissolution; such a condition characterizes the pore waters at present in sulphate-poor Buttle Lake, B.C. Under the existing conditions in Anderson Lake, Fe^{2+} must be diffusing upward from the natural sediments at depth in AND-1 and consuming sulphide via precipitation of FeS or FeS_2 at intermediate depths. Because no concentration gradient exists for dissolved iron at the base of AND-3, there can be no similar upward diffusion from the natural sediments at this site. In this core high iron concentrations persist to almost 10 cm depth which may reflect continuing dissolution of trace fractions of oxyhydroxide associated with the tailings. Presumably, such dissolution is balanced by precipitation of sulphides.

The dissolved Zn, Cu and Pb profiles indicate clearly that the tailings at sites AND-2 and AND-3 are not releasing metals to the overlying water column at present. In fact, the opposite phenomenon must be occurring - metals are diffusing into the tailings and being fixed into the solid phase at very shallow depths. Presumably, this extraction is attributable to precipitation of authigenic discrete or mixed sulphide phases, given the anoxic state of the deposits very near the interface. Such minerals are extremely insoluble in the presence of HS- (Jacobs and Emerson 1982), which explains why the concentrations at depth in the cores are so low (Appendix D).

At Site AND-1, the decreases with depth of the Cu and Pb concentrations are less abrupt that at the other locations. Why this should be the case is not clear, but it may be related to a speciation or complexation effect. The sediments in Core AND-1 are very organic-rich, and it would be expected that the associated pore waters contain more dissolved carbon than at the other two locations. The dissolved organic compounds (presumably humic and fulvic acids) will tend to keep metals in solution as soluble complexes. In slightly acid waters, such as Anderson lake water and presumably pore water, Zn^{2+} has a significantly lower affinity for organic ligands in solution than does Cu^{2+} or Pb^{2+} (Stumm and Morgan 1981) and competition between dissolved sulphide and the dissolved organic ligands will determine at which depth solid-phase sulphides will precipitate, given that the HS- concentration must initially increase with depth. Thus, Zn should precipitate as a sulphide first, given its relative aversion to complexation with organic compounds, followed by Pb and then Cu. The distributions in Core AND-1 are entirely consistent with this qualitative model as can be seen by comparing Figures 3-14 to 3-15 and examining the data in Appendix D.

5 - Conclusions

5.0 CONCLUSIONS

1. Mine tailings are widely distributed on the floor of Anderson Lake, occurring not only near the discharge outfall but also in distal regions, as demonstrated by the measurement of high Zn, Cu, Pb, Co and sulphur concentrations at shallow sub-bottom depths at a location (AND-1) some two kilometres from the discharge point.
2. Natural sediments underlying the tailings are extremely organic-rich, with organic carbon concentrations commonly exceeding 20 wt. %.
3. High dissolved iron concentrations (relative to bottom water) within five millimetres of the interface indicate that both the tailings and the natural sediment facies are suboxic or anoxic at very shallow sub-bottom depths.
4. Dissolved metal and sulphate concentrations are relatively high in Anderson Lake water but levels are below the regulatory limits at the lake outfall. These concentrations reflect contamination from metal-rich tailings-slurry water and from acid drainage emanating from a roadway along the north shore of the lake. Tailings were used in the construction of the roadway in the past.
5. Despite the high metal levels in the lake water, the concentrations of Zn, Cu and Pb in pore waters in both the tailings and natural sediment facies are extremely low. These depletions cannot be attributed to a non-steady-state effect but must reflect dynamic removal of metals from interstitial solution at very shallow depths at all sites. Such removal most probably reflects precipitation of authigenic discrete or mixed metal sulphide phases. The pore water profiles indicate that the depth at which precipitation occurs is on the order of a few millimetres at the sites of current or recent tailings discharge (AND-2 and AND-3), and on the order of a few centimetres to a decimetre in the distal natural sediment facies represented by Core AND-3.
6. There is no indication that the tailings on the floor of Anderson Lake are releasing Zn, Cu or Pb to the overlying lake water. In fact, the data presented in this report demonstrate unequivocally that metals are diffusing *into* the tailings and natural sediments from metal-rich bottom water.

7. It is expected that once mining ceases in the area and tailings are no longer discharged to Anderson Lake, organic-rich deposits will progressively blanket the tailings. This is already occurring at Site AND-2, formerly near the discharge pipeline (which has since been moved). The addition of a natural covering rich in organic matter should ensure that the tailings remain stored in a thermodynamically-stable anoxic state essentially in perpetuity.

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Appendix A: Detailed Core Descriptions

APPENDIX A: DETAILED CORE DESCRIPTIONS

CORE AND-1 (Eastern Arm)

62.5 cm total length, 3.1 m water depth. Good core, interface slightly disturbed (fine organic "fluff" dispersed in core-top water on recovery). Organic-rich, apparently natural sediments throughout.

Log Description:

0-2.5 cm: grayish-brown organic fluff with rusty and black specks.

2.5-10 cm: grades to grayish-brown gelatinous ooze.

10-12 cm: grades to homogeneous pale-brown gelatinous ooze with occasional black specks.

12-62.5 (end): homogeneous to bottom, pale brown to orangey-brown. At 21 cm, two cylindrical, vertical holes with dark brown haloes observed. Origin unknown, but they may be preserved worm burrows. In the 40-44 cm interval, abundant plant stems, fibres observed.

CORE AND-2 (Western Arm)

61.5 cm total length, 3.2 m water depth. Excellent core, undisturbed interface, very slightly domed. Zooplankton swimming near bottom in supernatant. About 1 cm of fine-grained organic-rich natural sediments overlying grayish-black, silt-sized tailings.

Log Description:

0-1 cm: organic-rich chocolate-brown silt with some intermixed tailings.

1-2 cm: mostly grayish-black, coarse-silt-sized tailings.

2-61.5 (end): homogeneous, grayish-black silt-sized tailings.

CORE AND-3 (Near Tailings Outfall)

41 cm total length, 6.1 m water depth. Excellent core, undisturbed interface - no resuspension (crystal-clear supernatant), very slight doming (about 5 mm relief on interface). Thin (few mm) organic-rich veneer overlying about a decimetre of gray silt-sized tailings, in turn overlying pale chocolate-brown, organic-rich natural sediments.

Log Description:

0-0.3 cm: orange-to-chocolate-brown organic-rich fine-silt-to clay-sized natural sediments.

0.3-3.3 cm: very-fine-silt-sized tailings, dark gray, lustrous (pyrite sheen), slightly laminated.

3.3-7 cm: fine-to-medium silt-sized tailings, mottled and darker gray than above interval.

7-13 cm: blackish-gray transition zone, mixed natural sediments and tailings, occasional black specks. Load casting of tailings on natural deposits observed in the 8-10 cm interval. Possible presence of methane at about 7 cm depth. Almost entirely natural sediments from 10 cm on. Cylindrical, vertical tubes (worm tubes?) occur at about 10 cm.

13-41 cm: homogeneous, pale chocolate-brown (10YR4/2) fine-grained natural sediments with occasional black specks (of organic origin?). Worm tubes(?) relatively common to about 22 cm, much less common in the 22-25 cm interval, and absent below 25 cm.

Appendix B: Analytical Methods & Quality Control Data

APPENDIX B: ANALYTICAL METHODS & QUALITY CONTROL DATA

Graphite Furnace Atomic Absorption Analysis

Dissolved metal concentrations in pore waters were determined by direct-injection graphite-furnace atomic absorption spectrophotometry using a Varian SpectrAA 300 spectrophotometer with Zeeman background correction and a PSD 96 autosampler. All determinations were conducted using pyrolitic L'Vov platforms using peak area measurements and operating conditions adapted from those recommended by the manufacturer. The autosampler was controlled by a Varian Quality Control program which ensured reproducibility. Standards were prepared by diluting 1000 ppm standard solutions with 1% twice-quartz-distilled HNO_3 in distilled deionized water. Where pore water metal concentrations were outside the linear calibration range, samples were diluted automatically by the autosampler with the same 1% HNO_3 and rerun.

Analytical precision estimates and the detection limit for each metal, defined in this study as three times the standard deviation of the mean of several blank determinations, are listed in Table B-1.

X-Ray Fluorescence Analysis

Following freeze-drying and grinding of the sediment samples to fine powders in a tungsten carbide disc mill, major and minor element concentrations were respectively measured on cast glass and pressed powder discs, using an automated Philips PW 1400 X-ray fluorescence spectrometer equipped with a Rh target anode. Glass discs were prepared using a slight modification of the method of Norrish and Hutton (1970), which eliminates the need to apply specific corrections for matrix absorption effects. The samples from AND-1 were extremely rich in organic matter which diluted the silicate content to the point where an amorphous glass would not form; the melt repeatedly shattered on cooling for most of the samples in the core. Thus, measurements of the major elements are sparse in that core only.

For minor elements, a method similar to that described by Harvey and Atkin (1982) was used. The samples were prepared by forming a mixture of 4 g sample and 0.5 g finely-divided wax (Hoechst Wax C) into 32-mm diameter discs in a hydraulic press.

Table B-1

Quality Control Data for GFAAS Measurement of Dissolved Metal Concentrations in Mandy and Anderson Lake Pore Waters, Analysed Concurrently in July and August 1990

Sample (Method)	Mn	Fe	Cu	Zn	Pb
M-07 (Normal)	14.1		158	344	20.4
M-07 (Normal)	13.3		164	310	21.4
M-07 (Std. Addition)				375	
M-27 (Normal)		15.7	7.9	39.0	0.9
M-27 (Normal)		15.9	13	36.4	0.9
M-27 (Std. Addition)			11	41.1	
A-41 (Normal)		135			
A-41 (Normal)		131			
Detection limit	4.5	48	8.3	1.2	1.4

Cu, Zn and Pb measurements are reported in nmol L^{-1} , and Mn and Fe in µmol L^{-1}. ***Normal = measurement by comparison to the linear calibration curve. Accuracy can be*** **assessed by comparing the results determined by normal calibration and by standard additions (where sample size permitted). Detection limit is defined as three times the standard deviation of a suite of deionized-water blanks run randomly with the analyses. All detection limits are given in nmol L^{-1}. Note that many pore water samples contained less dissolved Pb and Cu than our calculated detection limit (Table D-1). This means that such pore waters contain less of these dissolved metals than three times the standard deviation of GFAAS measurements made on our high purity distilled deionized laboratory water.**

Calibration for both sets of measurements was provided by a wide range of international geochemical reference standards, with discs prepared in the appropriate way, and using the element concentrations recommended by Abbey (1983). Additional metal-rich standards were prepared for the minor element measurements on the tailings-bearing samples, to ensure that a calibration curve could be used which was linear up to and beyond the maximum Zn, Cu or Pb concentration encountered. The highest concentrations in the synthetic standards were 96000 $\mu g\ g^{-1}$ Zn, 19000 $\mu g\ g^{-1}$ Cu and 4300 $\mu g\ g^{-1}$ Pb.

Analytical precision was estimated for major elements by comparing duplicate discs made for reference sample G2 (Table B-2). Accuracy was assessed by randomly including several geochemical reference samples as unknowns in the analytical run. The results of these measurements are listed in Table B-3. As can be seen the accuracy of the major element measurements is excellent.

CNS and $CaCO_3$ Analysis

Total carbon, nitrogen and sulphur were determined using elemental analysis. Total C and N were measured using a Carlo-Erba 1106 Elemental Analyzer which combusts the sample in a stream of O_2, separates the combustion gases (CO_2 and N2 reduced from NOx) chromatographically, and measures the gas concentrations (thus C and N contents) by thermal conductivity. Sulphur was determined using a Carlo-Erba NA-1500 CNS Analyzer, which employs the same methodology. The use of the two different instruments was required because the high sulphur content of the tailings swamped the C and N channels on the CNS Analyzer with SO_2. The analyzers are calibrated using acetanilide and the NRC marine sediment standards MESS-1 and BCSS-1. Accuracy is excellent; agreement with the recommended values for total C and N is always within analytical precision. The precision of the measurements (1σ, R.S.D.) was about 1.5%, 3% and 3% for C,N and S respectively.

Carbonate carbon was determined on all samples by coulometry using a Coulometrics Analyzer, which electrochemically measures the CO_2 evolved following addition of HCl to a sample. Concentrations were very low in the natural sediments (typically <0.1 wt.%), but ranged up to 0.8 wt. % in the tailings. Precision of the measurements (1σ, R.S.D.) was better than 3% for the higher carbonate carbon concentrations.

Table B-2

XRF Major Element Quality Control Data

Standard		Fe	Ti	Ca	K	Si	Al	Mg	P	Na
NIMS	(m)	0.95	0.00	0.46	9.39	30.03	9.37	0.28	0.052	0.20
	(r)	0.98	0.02	0.49	9.81	29.71	9.17	0.28	0.05	0.16
JR1	(m)	0.58	0.042	0.48	2.72	35.43	6.92	0.08	0.009	1.67
	(r)	0.67	0.06	0.45	2.82	35.22	6.82	0.05	0.01	1.48
JF2	(m)	0.0	0.0	0.07	8.01	30.42	10.04	0.00	0.000	1.05
	(r)	0.04	<0.01	0.06	8.37	30.44	9.75	0.003	<0.01	0.91
JG1A	(m)	1.38	0.132	1.51	2.47	34.25	7.71	0.45	0.035	1.46
	(r)	1.44	0.15	1.52	2.56	33.71	7.52	0.41	0.3	1.26
W2	(m)	7.52	0.618	7.66	0.41	23.87	7.97	3.91	0.057	0.93
	(r)	7.60	0.64	7.79	0.40	24.66	8.19	3.85	0.06	0.82
G2	(m)	1.83	0.31	1.37	2.77	32.16	8.22	0.55	0.06	1.65
G2 (Repeat)		1.83	0.30	1.37	2.79	32.32	8.09	0.49	0.06	1.51
	(r)	1.88	0.29	1.40	2.85	32.32	8.15	0.45	0.06	1.51

Concentrations determined for geochemical reference standards in this study (m) are compared with concentrations recommended (r) by Abbey (1980).

Table B-3

XRF Minor Element Quality Control Data

Standard		Zr ppm	Sr ppm	Rb ppm	Pb ppm	Zn ppm	Cu ppm	Ni ppm	Co ppm	Mn ppm	V ppm	Cr ppm	Ba ppm
SY2	(m)	269	236	166	87	250	7	41	12	2468	43	1	n.a.
	(r)	280	275	220	80	250	5	10	11	2480	52	12	460
BHVO	(m)	182	392	12	10	111	153	129	46	1307	354	311	n.a.
	(r)	180	420	10	n.a.	105	140	120	45	1316	300	320	135
W2	(m)	99	195	23	10	85	121	76	42	1225	279	95	n.a.
	(r)	100	190	21	n.a.	80	105	70	43	1300	260	92	175
NIMD	(m)	9	7	1	1	89	5	2031	245	1669	27	2483	n.a.
	(r)	20	3?	?	7?	90	10	2050	210	1690	40	2900	10?
MRG1	(m)	109	270	12	9	204	148	154	94	1168	360	465	n.a.
	(r)	92	178	17	n.a.	139	140	120	69	1031	326	408	10
NIMG	(m)	281	15	315	40	52	8	40	5	181	0	8	169
	(r)	300	10	320	40	50	12	8?	4?	162	2?	12	120?
NIMS	(m)	29	67	520	2	16	18	0	4	134	30	7	2501
	(r)	33	62	530	5	10	19	7	4	80	10	12	2400

Concentrations determined for geochemical reference standards in this study (m) are compared with concentrations recommended (r) by Abbey (1980). Qustion marks indicate possibly unreliable values; n.a. = not available.

Organic carbon was determined by subtracting carbonate carbon from the total C measurements. Precision of the resulting organic C value was about ±5 % (1σ, R.S.D.).

Appendix C: Sediment Chemistry Data

APPENDIX C: SEDIMENT CHEMISTRY DATA

Table C-1

Major Element Composition in Sediments from Three Anderson Lake Cores

Interval cm	Depth cm	Fe Wt. %	Ti Wt. %	Ca Wt. %	K Wt. %	Si Wt. %	Al Wt. %	Mg Wt. %	P Wt. %	Na Wt. %
CORE AND-1										
0-0.5	0.25*									
0.5-1	0.75*									
1-1.5	1.25*									
1.5-2	1.75	4.42	0.14	1.99	0.59	10.75	2.67	0.66	0.10	0.41
2-3	2.5	10.60	0.13	1.96	0.49	13.00	2.79	1.07	0.04	0.38
3-4	3.5*									
4-5	4.5*									
5-6	5.5*									
6-8	7*									
8-10	9*									
12-14	13*									
16-18	17*									
22-26	24*									
30-34	32	2.05	0.17	1.74	0.83	16.10	3.57	0.77	0.07	0.30
40-44	42*									
50-54	52*									
CORE AND-2										
0-0.5	0.25	26.58	0.13	1.08	0.66	14.98	4.08	1.41	0.05	0.28
0.5-1	0.75	28.49	0.11	1.07	0.59	15.14	4.07	1.44	0.04	0.29
1-2	1.5	29.95	0.10	1.19	0.56	14.83	3.80	1.35	0.03	0.25
2-3	2.5	24.44	0.13	1.72	0.77	17.30	4.60	1.88	0.04	0.29
3-4	3.5	20.41	0.15	2.02	0.96	18.99	5.37	2.27	0.04	0.33
4-5	4.5	21.84	0.14	1.97	0.88	18.65	5.12	2.10	0.04	0.29
5-6	5.5	22.23	0.13	1.97	0.86	18.22	4.94	1.91	0.03	0.31
6-7	6.5	23.67	0.13	1.79	0.71	17.84	4.53	1.65	0.03	0.30
7-9	8	25.89	0.10	1.76	0.71	17.81	4.68	1.63	0.03	0.22
9-11	10	24.61	0.10	2.16	0.58	16.40	4.13	1.50	0.03	0.28
13-15	14	26.64	0.11	1.87	0.54	16.70	4.27	1.62	0.03	0.30
17-19	18	25.93	0.10	2.06	0.63	16.45	4.22	1.76	0.03	0.30
23-27	24.5	13.62	0.14	3.74	1.09	21.18	5.71	3.15	0.03	0.36
33-37	34.5	21.83	0.10	1.69	0.68	20.58	4.31	1.53	0.02	0.28
43-47	44.5	31.24	0.08	1.06	0.40	15.78	3.34	1.12	0.02	0.26
53-57	54.5	10.35	0.18	2.77	1.17	25.10	6.25	3.04	0.03	0.43

*Asterisks indicate samples for which glass discs repeatedly shattered on cooling; no measurements could be made on these samples.

Table C-1 (continued...)

Major Element Composition in Sediments from Three Anderson Lake Cores

Interval cm	Depth cm	Fe Wt. %	Ti Wt. %	Ca Wt. %	K Wt. %	Si Wt. %	Al Wt. %	Mg Wt. %	P Wt. %	Na Wt. %
CORE AND-3										
0-0.5	0.25	25.44	0.10	1.42	0.65	13.51	4.23	1.72	0.03	0.27
0.5-1	0.75	25.40	0.11	1.57	0.61	13.06	4.04	1.72	0.03	0.23
1-1.5	1.25	24.87	0.11	1.39	0.66	13.89	4.37	1.91	0.03	0.34
1.5-2	1.75	26.87	0.11	1.39	0.47	13.36	3.79	2.01	0.03	0.37
2-3	2.5	28.00	0.10	1.37	0.45	12.36	3.49	1.90	0.04	0.32
3-4	3.5	25.03	0.13	1.21	0.57	14.14	4.19	1.74	0.06	0.30
4-5	4.5	22.83	0.14	1.28	0.70	14.66	4.69	1.66	0.08	0.33
5-6	5.5	20.24	0.14	1.39	0.73	14.95	4.61	1.60	0.10	0.31
6-8	7	17.92	0.16	1.49	0.75	14.91	4.67	1.51	0.12	0.37
8-10	9	14.34	0.16	1.51	0.81	14.64	4.49	1.31	0.12	0.30
10-12	11	10.25	0.18	1.55	0.84	14.75	4.40	1.15	0.13	0.34
12-14	13	8.75	0.19	1.55	0.92	15.15	4.42	1.12	0.14	0.36
14-16	15	6.36	0.21	1.60	1.03	15.83	4.63	1.02	0.13	0.48
16-18	17	4.12	0.22	1.59	1.14	15.08	4.33	0.90	0.12	0.32
18-20	19	4.07	0.25	1.62	1.18	16.16	5.16	1.06	0.12	0.41
20-22	21	5.31	0.25	1.57	1.21	15.98	5.33	1.16	0.11	0.84
22-25	23.5*									
25-28	26.5	3.36	0.28	1.61	1.33	17.10	5.61	1.22	0.10	0.43
28-31	29.5	3.61	0.28	1.52	1.26	17.50	5.66	1.18	0.10	0.41
34-37	35.5	3.51	0.28	1.38	1.28	17.15	5.62	1.24	0.09	0.44

*Asterisks indicate samples for which glass discs repeatedly shattered on cooling; no measurements could be made on these samples.

Table C-2

Major Element Weight Ratios in Sediments from Three Anderson Lake Cores

Interval cm	Depth cm	Fe/Al Wt. Ratio	Ti/Al Wt. Ratio	Ca/Al Wt. Ratio	K/Al Wt. Ratio	Si/Al Wt. Ratio	Mg/Al Wt. Ratio	Na/Al Wt. Ratio
CORE AND-1								
0-0.5	0.25*							
0.5-1	0.75*							
1-1.5	1.25*							
1.5-2	1.75	1.65	0.052	0.74	0.22	4.02	0.25	0.15
2-3	2.5	3.79	0.047	0.70	0.17	4.65	0.38	0.14
3-4	3.5*							
4-5	4.5*							
5-6	5.5*							
6-8	7*							
8-10	9*							
12-14	13*							
16-18	17*							
22-26	24*							
30-34	32	0.57	0.049	0.49	0.23	4.51	0.22	0.084
40-44	42*							
50-54	52*							
CORE AND-2								
0-0.5	0.25	6.51	0.031	0.26	0.16	3.67	0.35	0.069
0.5-1	0.75	7.00	0.027	0.26	0.15	3.72	0.35	0.070
1-2	1.5	7.88	0.025	0.31	0.15	3.90	0.36	0.066
2-3	2.5	5.32	0.029	0.37	0.17	3.76	0.41	0.063
3-4	3.5	3.80	0.028	0.38	0.18	3.54	0.42	0.062
4-5	4.5	4.27	0.027	0.38	0.17	3.65	0.41	0.056
5-6	5.5	4.50	0.027	0.40	0.17	3.69	0.39	0.062
6-7	6.5	5.22	0.028	0.39	0.16	3.94	0.36	0.065
7-9	8	5.53	0.022	0.38	0.15	3.80	0.35	0.048
9-11	10	5.96	0.025	0.52	0.14	3.97	0.36	0.067
13-15	14	6.24	0.027	0.44	0.13	3.91	0.38	0.070
17-19	18	6.15	0.023	0.49	0.15	3.90	0.42	0.072
23-27	24.5	2.39	0.025	0.66	0.19	3.71	0.55	0.064
33-37	34.5	5.07	0.024	0.39	0.16	4.78	0.36	0.065
43-47	44.5	9.36	0.023	0.32	0.12	4.73	0.33	0.078
53-57	54.5	1.66	0.029	0.44	0.19	4.02	0.49	0.069

***Asterisks indicate samples for which glass discs repeatedly shattered on cooling; no measurements could be made on these samples.**

Table C-2 (continued...)

Major Element Weight Ratios in Sediments from Three Anderson Lake Cores

Interval cm	Depth cm	Fe/Al Wt. Ratio	Ti/Al Wt. Ratio	Ca/Al Wt. Ratio	K/Al Wt. Ratio	Si/Al Wt. Ratio	Mg/Al Wt. Ratio	Na/Al Wt. Ratio
CORE AND-3								
0-0.5	0.25	6.02	0.023	0.34	0.15	3.20	0.41	0.063
0.5-1	0.75	6.29	0.028	0.39	0.15	3.23	0.43	0.057
1-1.5	1.25	5.69	0.026	0.32	0.15	3.17	0.44	0.077
1.5-2	1.75	7.08	0.030	0.37	0.12	3.52	0.53	0.099
2-3	2.5	8.03	0.029	0.39	0.13	3.54	0.54	0.092
3-4	3.5	5.97	0.032	0.29	0.14	3.37	0.41	0.073
4-5	4.5	4.87	0.031	0.27	0.15	3.13	0.36	0.070
5-6	5.5	4.39	0.030	0.30	0.16	3.25	0.35	0.068
6-8	7	3.84	0.033	0.32	0.16	3.19	0.32	0.079
8-10	9	3.20	0.035	0.34	0.18	3.26	0.29	0.066
10-12	11	2.33	0.041	0.35	0.19	3.35	0.26	0.077
12-14	13	1.98	0.043	0.35	0.21	3.43	0.25	0.082
14-16	15	1.37	0.045	0.35	0.22	3.42	0.22	0.103
16-18	17	0.95	0.051	0.37	0.26	3.48	0.21	0.074
18-20	19	0.79	0.049	0.31	0.23	3.13	0.20	0.079
20-22	21	1.00	0.047	0.30	0.23	3.00	0.22	0.158
22-25	23.5*							
25-28	26.5	0.60	0.050	0.29	0.24	3.05	0.22	0.077
28-31	29.5	0.64	0.050	0.27	0.22	3.09	0.21	0.072
34-37	35.5	0.62	0.049	0.25	0.23	3.05	0.22	0.079

*Asterisks indicate samples for which glass discs repeatedly shattered on cooling; no measurements could be made on these samples.

Table C-3

Minor Element Composition of Sediments in Three Anderson Lake Cores

Interval cm	Depth cm	Zr ppm	Y ppm	Sr ppm	Rb ppm	Pb ppm	Zn ppm	Cu ppm	Ni ppm	Co ppm	Mn ppm	V ppm	Cr ppm	Ba ppm
CORE	**AND-1**													
0-0.5	0.25	76	9	58	32	715	8809	2413	37	91	532	75	51	471
0.5-1	0.75	75	11	66	35	601	7099	2327	52	141	543	70	54	518
1-1.5	1.25	79	11	73	34	479	5363	2173	50	103	485	65	52	489
2-3	2.5	46	6	16	15	580	94482	14434	32	245	721	37	21	263
3-4	3.5	48	9	6	7	599	121345	19094	36	230	857	36	19	272
4-5	4.5	72	10	76	39	296	2596	1688	36	73	396	53	50	426
5-6	5.5	71	12	68	33	279	9846	2686	40	126	451	65	57	407
6-8	7	65	6	64	38	232	1551	1113	28	70	306	44	38	391
8-10	9	66	6	65	32	164	1006	779	30	60	276	49	40	361
12-14	13	63	5	66	36	29	553	110	41	49	255	61	44	354
16-18	17	61	4	72	36	25	380	87	41	51	264	53	45	357
22-26	24	62	10	70	34	5	199	31	35	36	271	55	40	366
30-34	32	65	10	73	47	3	68	9	25	11	369	76	78	422
40-44	42	110	15	107	76	17	124	18	62	39	579	124	109	748
50-54	52	109	20	99	73	14	117	22	57	38	547	114	102	615
CORE	**AND-2**													
0-0.5	0.25	73	13	21	9	460	13272	1977	21	201	900	46	18	198
0.5-1	0.75	73	15	51	11	561	12620	1981	25	470	689	23	17	124
1-2	1.5	64	13	45	8	400	12726	1792	22	529	695	18	67	116
2-3	2.5	74	18	65	17	401	11759	1430	33	365	979	32	26	141
3-4	3.5	90	18	84	20	454	8536	1398	29	223	1263	53	44	178
4-5	4.5	86	18	76	19	469	9410	1554	30	286	1175	47	74	160
5-6	5.5	81	18	69	16	570	11320	1421	35	324	1140	47	35	152
6-7	6.5	69	15	56	14	518	9657	1096	19	379	970	35	35	131
7-9	8	60	12	54	12	487	8103	1097	22	400	851	32	68	134
9-11	10	60	17	60	5	499	10370	1115	32	448	1100	45	90	127
13-15	14	56	13	60	10	457	8457	1039	24	389	1045	41	131	112
17-19	18	54	14	53	6	480	8116	1319	30	372	956	27	107	111
23-27	24.5	91	19	92	25	755	3374	777	17	55	2255	59	35	198
33-37	34.5	49	9	62	16	544	7126	735	13	201	806	50	42	124
43-47	44.5	34	7	41	8	294	7132	1116	23	402	534	14	70	88
53-57	54.5	89	15	108	30	682	2899	570	17	29	1718	104	57	223

n.d. = not detectable

Table C-3 (continued...)

Minor Element Composition of Sediments in Three Anderson Lake Cores

Interval cm	Depth cm	Zr ppm	Y ppm	Sr ppm	Rb ppm	Pb ppm	Zn ppm	Cu ppm	Ni ppm	Co ppm	Mn ppm	V ppm	Cr ppm	Ba ppm
CORE AND-3														
0-0.5	0.25	97	17	47	2	2383	23256	2204	26	345	539	11	20	124
0.5-1	0.75	99	17	42	n.d.	2903	22938	2041	26	366	650	27	19	148
1-1.5	1.25	98	14	43	n.d.	3477	22932	1999	25	346	612	27	37	142
1.5-2	1.75	95	13	35	n.d.	4806	29648	2523	37	446	638	14	52	101
2-3	2.5	82	11	36	n.d.	3678	34966	2903	30	411	589	17	66	91
3-4	3.5	98	17	51	n.d.	2015	22339	3198	25	368	636	33	75	118
4-5	4.5	106	20	59	10	1231	17587	3593	28	363	707	36	68	147
5-6	5.5	94	17	55	13	1079	15080	4611	24	306	694	41	29	177
6-8	7	87	15	61	19	1024	15530	5848	32	292	675	41	26	172
8-10	9	79	17	73	32	774	11493	3918	37	204	617	51	42	205
10-12	11	78	14	78	45	525	7009	2333	37	127	516	63	48	274
12-14	13	58	8	57	34	232	2399	680	23	54	385	51	45	255
14-16	15	81	13	91	61	183	1850	588	33	48	480	95	75	398
16-18	17	85	14	95	69	93	504	265	35	24	452	112	90	474
18-20	19	88	14	101	74	95	517	220	38	22	459	110	94	491
20-22	21	93	14	102	75	208	1522	366	40	37	502	110	93	471
22-25	23.5	96	13	105	80	7	114	24	39	34	534	125	105	582
25-28	26.5	100	16	107	81	8	107	16	40	14	583	128	106	570
28-31	29.5	107	16	112	86	8	116	24	44	16	628	125	107	585
34-37	35.5	102	15	106	87	12	107	17	39	15	646	125	107	580

n.d. = not detectable

Table C-4

Organic Carbon, Nitrogen, Sulphur and Calcium Carbonate Concentrations in Sediments from Three Anderson Lake Cores

Interval cm	Depth cm	$CaCO_3$ Wt. %	N Wt. %	S Wt. %	C_{org} Wt. %	C/N Wt. Ratio
CORE AND-1						
0-0.5	0.25	0.59	1.73	4.94	19.10	11.1
0.5-1	0.75	0.09	1.74	4.38	20.65	11.9
1-1.5	1.25	0.17	1.88	3.68	22.77	12.1
1.5-2	1.75	0.03	1.96	3.25	24.15	12.4
2-3	2.5	3.95	1.12	12.77	14.43	12.8
3-4	3.5	5.28	0.89	14.94	11.37	12.8
4-5	4.5	0.09	2.14	2.76	26.44	12.4
5-6	5.5	0.15	2.10	3.30	26.16	12.5
6-8	7	0.03	2.26	2.69	28.03	12.4
8-10	9	0.05	2.31	2.53	28.06	12.1
12-14	13	0.00	2.29	2.14	27.65	12.1
16-18	17	0.04	2.31	1.99	28.20	12.2
22-26	24	0.04	2.25	1.66	27.84	12.4
30-34	32	0.06	2.07	1.22	25.90	12.5
40-44	42	0.03	2.29	0.82	27.36	12.0
50-54	52	0.00	1.98	0.64	24.92	12.6
CORE AND-2						
0-0.5	0.25	0.23	0.20	18.25	2.15	11.0
0.5-1	0.75	0.54	0.12	21.14	1.26	10.7
1-2	1.5	1.55	0.06	23.44	0.61	9.8
2-3	2.5	2.66	0.04	19.59	0.29	7.5
3-4	3.5	2.90	0.03	16.66	0.23	8.3
4-5	4.5	3.02	0.00	17.83	0.20	-
5-6	5.5	3.05	0.00	19.14	0.17	-
6-7	6.5	2.58	0.04	21.18	0.24	6.0
7-9	8	2.70	0.04	22.47	0.23	6.5
9-11	10	3.67	0.00	21.80	0.15	-
13-15	14	2.33	0.00	20.78	0.30	-
17-19	18	3.51	0.07	21.35	0.42	6.0
23-27	24.5	7.34	0.02	12.49	0.18	8.0
33-37	34.5	2.01	0.00	16.00	0.37	-
43-47	44.5	1.36	0.03	22.58	0.15	5.4
53-57	54.5	4.33	0.03	7.91	0.12	4.2

Table C-4 (continued...)

Organic Carbon, Nitrogen, Sulphur and Calcium Carbonate Concentrations in Sediments from Three Anderson Lake Cores

Interval cm	Depth cm	$CaCO_3$ Wt. %	N Wt. %	S Wt. %	C_{org} Wt. %	C/N Wt. Ratio
CORE AND-3						
0-0.5	0.25	2.23	0.11	23.11	1.14	10.2
0.5-1	0.75	2.57	0.04	24.01	0.36	8.9
1-1.5	1.25	2.21	0.02	24.52	0.18	7.6
1.5-2	1.75	2.52	0.02	26.28	0.21	8.6
2-3	2.5	2.39	0.05	26.71	0.51	10.4
3-4	3.5	0.89	0.17	22.05	1.79	10.3
4-5	4.5	0.53	0.30	19.83	3.05	10.1
5-6	5.5	0.23	0.57	15.50	5.30	9.2
6-8	7	0.27	0.85	13.97	7.50	8.9
8-10	9	0.25	1.24	11.03	11.01	8.9
10-12	11	0.14	1.64	8.03	14.99	9.1
12-14	13	0.11	1.73	6.55	16.34	9.5
14-16	15	0.15	1.87	3.84	18.22	9.7
16-18	17	0.07	1.98	1.87	19.42	9.8
18-20	19	0.07	1.97	1.71	19.20	9.7
20-22	21	0.06	1.83	2.62	18.12	9.9
22-25	23.5	0.13	1.74	0.65	18.07	10.4
25-28	26.5	0.08	1.76	0.50	18.82	10.7
28-31	29.5	0.02	1.61	0.45	17.72	11.0
34-37	35.5	0.02	1.58	0.42	17.65	11.1

Appendix D: Metals Analyses in Interstitial Waters

APPENDIX D: INTERSTITIAL WATER CHEMISTRY

Table D-1

Interstitial Water Chemistry of Three Anderson Lake Cores

Depth cm	Mn µmol L^{-1}	Fe µmol L^{-1}	Cu nmol L^{-1}	Pb nmol L^{-1}	Zn nmol L^{-1}
CORE AND-1					
-0.25	2.41	5.61	52.8	4.9	3133
0.25	2.64	12.7	23.2	4.8	198
0.75	2.61	152	40.0*	8.8*	79
1.25	2.59	6.55	33.4*	6.6*	64
1.75	2.46	1.86	18.7	3.3	105
2.5	1.20	3.58	35.6*	3.3	600*
3.5	2.99	4.82	20.9	3.0	26
4.5	3.14	3.92	23.2	3.7	32
5.5	3.43	1.90	17.9	2.2	173*
7	3.94	9.61	13.7	1.0	40
9	3.77	3.80	9.9	0.5	257*
13	4.08	3.01	3.3	0.1	36
17	4.49	6.80	1.6	0.0	14
24	6.66	16.6	2.0	0.1	39
32	8.26	19.2	0.0	0.0	16
42	10.76	23.8	4.9	0.0	271*
52	11.83	532	3.3	0.0	36
CORE AND-2					
-0.25	2.26	7.03	46.3	5.3	3152
0.25	2.76	114	5.8	1.8	511
0.75	2.76	116	0.5	0.4	143
1.5	3.06	140	2.2	0.0	79
2.5	4.60	114	0.0	0.0	78
3.5	5.20	8.04	0.0	0.0	83
4.5	5.82	3.65	0.0	0.0	55
5.5	5.80	0.31	0.0	0.0	32
6.5	5.67	0.15	0.0	0.0	38
8	5.88	1.96	0.0	0.0	15
10	4.50	2.94	0.0	0.0	11
14	3.30	0.17	0.0	0.0	17
18	2.18	0.27	0.0	0.0	13
25	1.12	0.17	0.0	1.1*	5
35	0.50	0.08	0.0	0.0	1
45	0.95	1.37	0.0	0.0	0
55	0.55	0.11	0.0	0.0	4

*Measurements marked with an asterisk are thought to reflect contamination, based on criteria defined in the text.

Table D-1 (continued...)
Interstitial Water Chemistry of Three Anderson Lake Cores

Depth cm	Mn µmol L^{-1}	Fe µmol L^{-1}	Cu nmol L^{-1}	Pb nmol L^{-1}	Zn nmol L^{-1}
CORE AND-3					
-0.25	2.55	6.56	64.4	1.9	1225
0.25	4.14	77.1	8.0	0.1	33
0.75	5.68	141*	275.4*	137.2*	2735*
1.25	6.73	38.6	0.0	0.0	156
1.75	6.87	16.7	0.0	0.0	242
2.5	6.37	87.7	0.0	0.0	55
3.5	6.48	58.0	0.0	0.0	20
4.5	6.50	51.4	0.0	0.0	17
5.5	5.46	46.9	0.0	0.0	6
7	6.26	164	0.0	0.0	6
9	6.11	106	0.0	0.0	6
11	6.14	56.4	0.0	0.0	5
13	6.63	49	1.7*	0.6*	35*
15	6.38	25.0	0.0	0.1	11
17	6.51	37.8	0.0	0.2	6
19	8.81	46.7	0.0	0.2	5
21	11.0	67.4*	8.1*	2.4*	34*
23.5	12.7	51.1	0.6	0.0	4
26.5	15.6	41.6	0.0	0.0	6
29.5	16.2	41.1	1.0	0.1	7
35.5	14.5	49.2	3.0	0.1	8

*Measurements marked with an asterisk are thought to reflect contamination, based on criteria defined in the text.