CHEMICAL DIAGENESIS OF SUBMERGED MINE TAILINGS IN BENSON LAKE AND NATURAL SEDIMENTS IN KEOGH LAKE, VANCOUVER ISLAND, BRITISH COLUMBIA

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Chemical Diagenesis of Submerged Mine Tailings in Benson Lake and Natural Sediments in Keogh Lake, Vancouver Island, British-Columbia

An Acid Drainage Task Force Project in Contribution to MEND (Mine Environment Neutral Drainage)

Prepared for and Funded by:

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EXECUTIVE SUMMARY

Pyrite-rich mine tailings from the Coast Copper mine were discharged into Benson Lake from 1962 to 1973. The tailings in the central basin of the lake are now covered by about 30 cm of natural organic-rich sediments containing about 7 wt. % organic carbon. The relatively high C:N weight ratio (~22) indicates that the organic matter is largely of terrigenous origin. Nearby Keogh Lake, which was sampled to provide a control site, is in a different watershed and never received input of any mining-related discharges. Sediments in the centre of this basin contain ~11-22 wt. % organic carbon. The organic fraction had a C:N weight ratio ranging from 16-20 suggesting an origin which was partly terrigenous and partly planktonic.

One sediment core from each lake was collected (in August, 1991 in Benson Lake, and November, 1991 in Keogh) and processed under nitrogen to extract interstitial waters. Solid-phase elemental analyses and dissolved metals and sulphate determinations were made on sediment samples and pore waters, respectively . The Benson core consisted of about 30 cm of "natural" (but still copper-enriched) sediments overlying Cu-bearing but Zn- and Pb-deplete, sulphide-rich tailings. The Keogh Lake core consisted or organic-rich natural deposits punctuated by a six-centimetre thick grey clay layer between about 24 and 30 cm depth. A thin veneer of manganese and iron oxyhydroxide-rich material mantles the sediments in both basins. In Keogh, this layer appears to be at most 5 mm thick; in Benson, it may be slightly thicker.

High dissolved iron concentrations (relative to bottom water) at 1.5 cm depth in the Keogh deposits and below 1.5 cm in the Benson sediments indicate that the natural sediments are suboxic or anoxic at very shallow sub-bottom depths in both lakes.

Dissolved metal concentrations are low in the bottom waters of both lakes, being approximately equal to or less than B.C. MOE and/or CCREM guidelines. Sulphate levels are also very low, being <10 μmol L-1 (0.09 mg L^{-1}) in the bottom waters of both basins.

High-resolution profiles of dissolved Zn, Pb and Cd in the pore waters of both lakes show that concentrations of these metals decrease across the sediment-water interface, and are invariably lower than the levels measured in core-top (bottom) water. These data confirm that at the time of sampling there was no efflux of these metals to the overlying water in either basin. Profiles of the dissolved copper concentration in pore waters suggest that some Cu may be diagenetically cycled just below the sediment-water interface in the Keogh

deposits. Concentrations are low, however, and there was no indication of a benthic efflux of the metal. The Benson Lake profile yields a similar conclusion: there is no evidence of a benthic efflux of dissolved copper from the sediments to bottom waters in the lake despite the fact that the "natural" sediments accumulating at present, and progressively burying the tailings, still contain higher concentrations of solid-phase copper than would be expected in a pristine basin.

Des résidus miniers riches en pyrite provenant de la mine de cuivre Coast Copper ont été versés dans le lac Benson entre 1962 et 1973. Actuellement, les résidus qui se trouvent dans le bassin lacustre central sont recouverts d'environ 30 cm de sédiments naturels riches en matières organiques dont le pourcentage massique de carbone organique est approximativement 7. Le rapport C:N est relativement élevé (~22), ce qui indique que les matières organiques ont une origine largement terrigène. Le lac Keogh voisin, qui a servi d'emplacement témoin, fait partie d'un réseau hydrographique distinct et n'a jamais servi de bassin de réception de résidus miniers. Les sédiments provenant du centre du lac Keogh ont un pourcentage massique de carbone organique allant d'environ 11 à 22. Le rapport C:N de la fraction organique varie de 16 à 20, ce qui porte à croire que ces matières organiques sont en partie terrigènes et en partie planctoniques.

Une carotte de sédiments a été prélevée dans le lac Benson en août 1991 et une autre dans le lac Keogh en novembre 1991. Elles ont été traitées en atmosphère d'azote afin d'en extraire l'eau interstitielle. On a effectué des analyses élémentaires sur la phase solide des échantillons de sédiments, et on a déterminé les métaux dissous et la quantité de soufre dans l'eau interstitielle. La carotte en provenance du lac Benson comportait environ 30 cm de sédiments «naturels» (mais néanmoins enrichis en cuivre) qui reposaient sur des résidus cuprifères riches en sulfure et appauvris en Zn et en Pb. La carotte provenant du lac Keogh était composée de dépôts organiques naturels que recoupait une couche d'argile grise de 6 cm d'épaisseur à entre environ 24 et 30 cm de profondeur. Un placage de matériau riche en oxyhydroxyde de manganèse et de fer recouvre les sédiments dans les deux bassins; son épaisseur maximale semble être de 5 mm dans le lac Keogh et peut-être un peu plus dans le lac Benson.

Les concentrations élevées (par rapport aux eaux de fond) de fer dissous à une profondeur de 1,5 cm dans les dépôts du lac Keogh et de plus de 1,5 cm dans les sédiments du lac Benson, indiquent que les sédiments naturels sont suboxiques ou anoxiques à de très faibles profondeurs sous le fond des deux lacs.

Les concentrations de métaux dissous sont faibles dans les eaux de fond des deux lacs; elles sont à peu près égales ou inférieures aux chiffres établis dans les lignes directrices du ministère de l'Environnement de la C.-B. ou du CCME. Les teneurs en soufre sont très faibles, soit < 10 μmol L^{-1} (0,09 mg L^{-1}) dans les eaux de fond des deux bassins.

Des profils très précis de la distribution du Zn, du Pb et du Cd dissous dans l'eau interstitielle des deux lacs indiquent que les concentrations de ces métaux diminuent en traversant l'interface sédiment-eau et qu'elles sont invariablement moins élevées que les concentrations mesurées dans les eaux de fond (au sommet de la carotte). Ces données confirment qu'au moment de l'échantillonnage dans les deux bassins, il n'y avait aucun passage de métaux dans la tranche d'eau sus-jacente. Les profils des concentrations de cuivre dissous dans l'eau interstitielle portent à croire qu'il pourrait y avoir recyclage diagénétique d'une partie du Cu immédiatement sous l'interface sédiment-eau dans les dépôts du lac Keogh. Or, les concentrations sont faibles, et il n'existe aucune indication d'un passage benthique de ce métal. Le profil du lac Benson indique la même chose : il n'existe aucun indice de passage benthique du cuivre dissous des sédiments aux eaux de fond, et ce, malgré le fait que les sédiments «naturels» qui s'accumulent actuellement et qui recouvrent progressivement les résidus contiennent des concentrations plus élevées de cuivre en phase solide que ce que l'on s'attendrait à trouver dans un bassin propre.

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1.0 INTRODUCTION

The disposal 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 (Drysdale 1990, Pedersen 1983, Pedersen 1984, Pedersen 1985, Pedersen and Losher 1988, Pedersen *et al.* 1990, Rescan 1990a, b and c). The results accrued to-date reasonably illustrate 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 information on the long-term diagenetic activity of mine wastes, both in marine and lacustrine waters.

This report describes the chemical behaviour of Zn, Cu and Pb in tailings discharged in the past to the floor of Benson Lake, British Columbia and in natural sediments in nearby Keogh Lake. The latter was chosen as a pristine, hydrographically similar "control basin" in order to permit detailed geochemical comparison between tailings-replete and tailings-free sedimentary facies.

1.1 Environmental Setting and Background to the Study

The Benson Lake watershed is part of the Marble River drainage and is located in northern Vancouver Island, about 15 km east of the town of Port Alice (Figure 1-1). The drainage is primarily surrounded by a coastal western hemlock biogeoclimatic zone. MacMillan Bloedel Limited currently logs the Benson and Raging River drainages out of their Port McNeil division. Access to the region is excellent along active logging roads. The area is characterized by a moderate relief, limestone karst terrain, and has historically been the location of a number of mining operations. Benson Lake is considered to be oligotrophic, and contains relatively soft water (Rescan 1991). The lake consists of a

Keogh Lake

Project Location

Vancouver Island

Angler
Lake

Three

Three Isle
Lake

Lakes

Creek

Maynard Lake

Benson Lake

N

0   1000   2000
metres
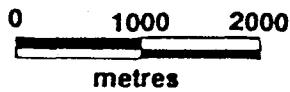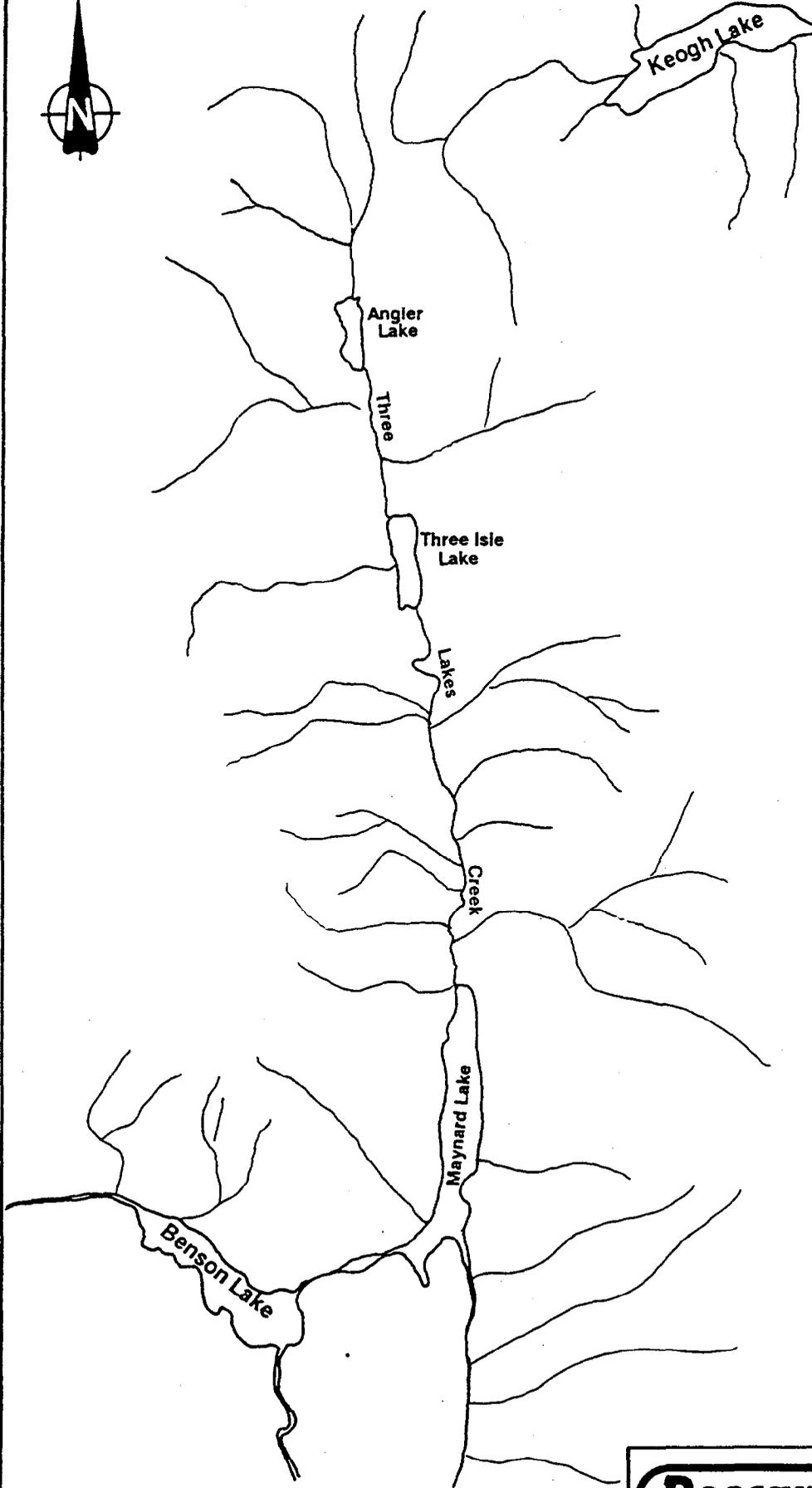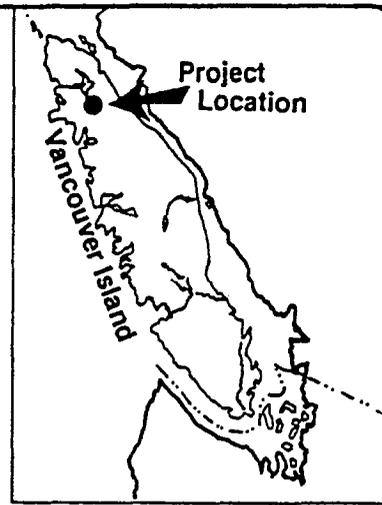
Rescan

RESCAN ENVIRONMENTAL SERVICES LTD.
VANCOUVER , B.C.   CANADA

Figure 1-1 Project Location

DWG :

DATE :

DB-R0021

single, sausage-shaped basin 2.2 km long (Figure 1-2), which reaches a maximum depth in the centre of ~54 m (Rescan 1991). The lake is fed from the eastern end by the Benson and Raging rivers (Figure 1-1); the Benson River continues as the outflow, draining in a westerly direction.

Keogh Lake is similar to Benson in size, shape and depth (Figure 1-3) and lies approximately 12 km to the northeast (see Figure 1-1). The lake forms the headwaters of the Keogh River which flows northwestward into Queen Charlotte Strait.

The Benson Lake Coast Copper Mine, owned by Cominco Ltd., commenced operations in August 1962 and operated until January 1973. The mine exploited two underground deposits and produced copper concentrate from high grade ore (mean grade 2.02 % Cu). In total 3.6 million tons of ore were processed at an average rate of 750-850 tpd. A magnetite recovery plant operated from March 1963 until September 1970 when unacceptably high sulphur contents in the concentrate forced closure. The mine discharged tailings into Benson Lake under permit because the local terrain was unfavorable to conventional land disposal into an impoundment. Discharge into Benson Lake was accomplished via a floating outfall.

Excessive turbidity was a persistent problem throughout the mine's operation (Kussat *et al.*, 1972; Hallam *et al.*, 1974). The tailings contained a slowly-settling colloidal fraction which apparently was never compositionally characterized (Rescan 1991). Attempts to mitigate the problem by adding various flocculants were unsuccessful. The tailings outfall was progressively moved to deeper water and after 1970, discharge occurred at a depth of 30.5 m. The deeper discharge depth did not resolve the turbidity problem, particularly during the winter months when the water column was isothermal. Hallam *et al.* (1974) attributed this to dispersal of the colloidal fraction of the tailings during the fall overturn event.

By 1967, the entire floor of the lake was covered by tailings and benthic invertebrates had been virtually eliminated (Kussat *et al.* 1972). Tailings fines were also present in the bottom of the outflowing Benson River. Resident fish in the lake were observed to feed preferentially on aquatic and terrestrial invertebrates found in drift entering from inlet streams. High zinc concentrations in both lake water and fish flesh were noted during the period of the mining operations; interestingly, similarly high Zn concentrations were found in fish from Maynard Lake, a control lake upstream which discharges into Benson Lake over a dam via the Raging River (Figure 1-1). This comparison is statistically

BENSON RIVER (out flow)

CRAFT CREEK (in flow)

LEGEND

⊙ Location of Core, August 1991.

10
20
30
30
40
50

0   100   200   300   400
METRES

RAGING RIVER (in flow)

BENSON RIVER (in flow)

40 30 20 10

Gill Net set 1
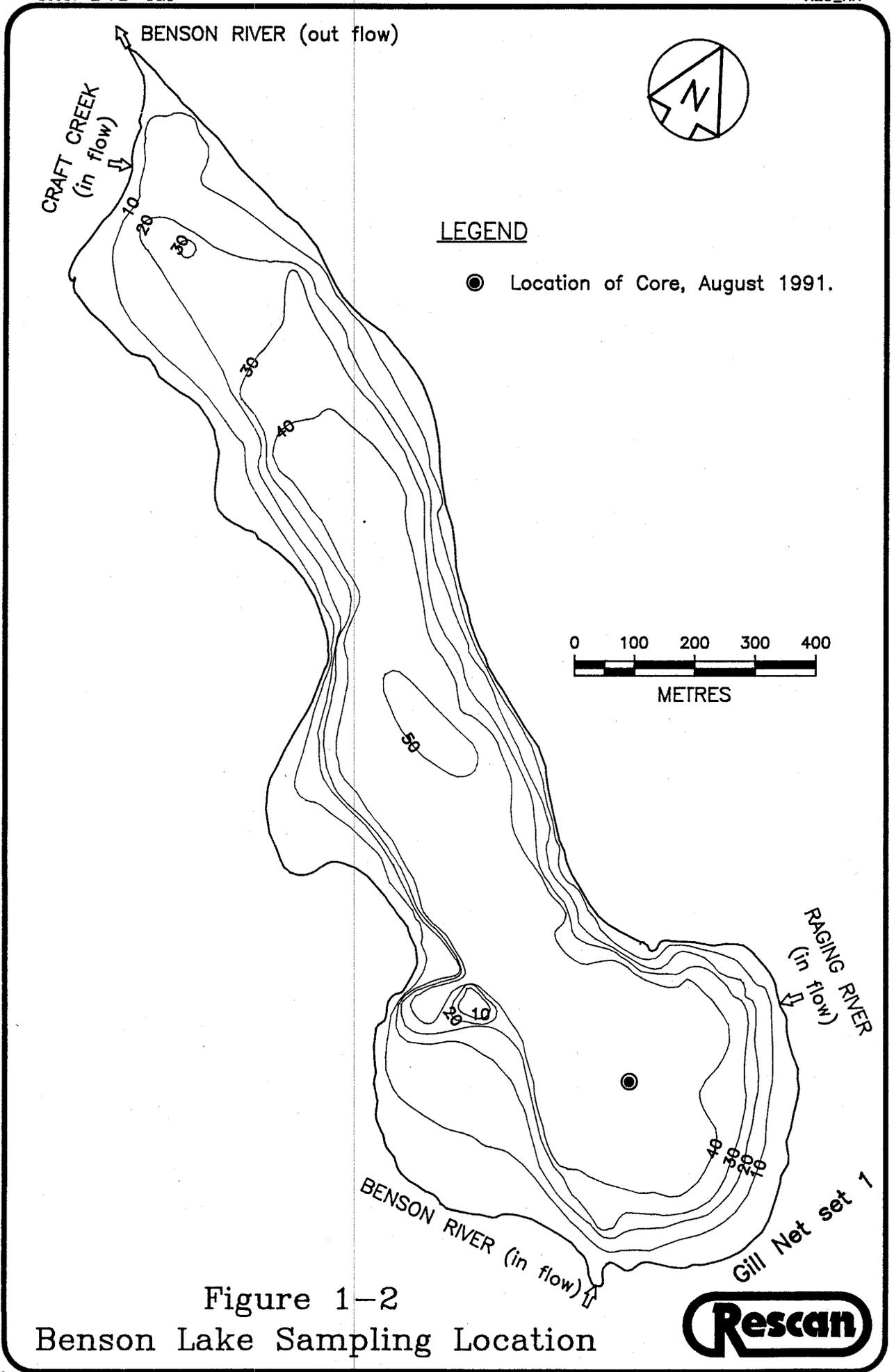
Figure 1-2
Benson Lake Sampling Location

Rescan
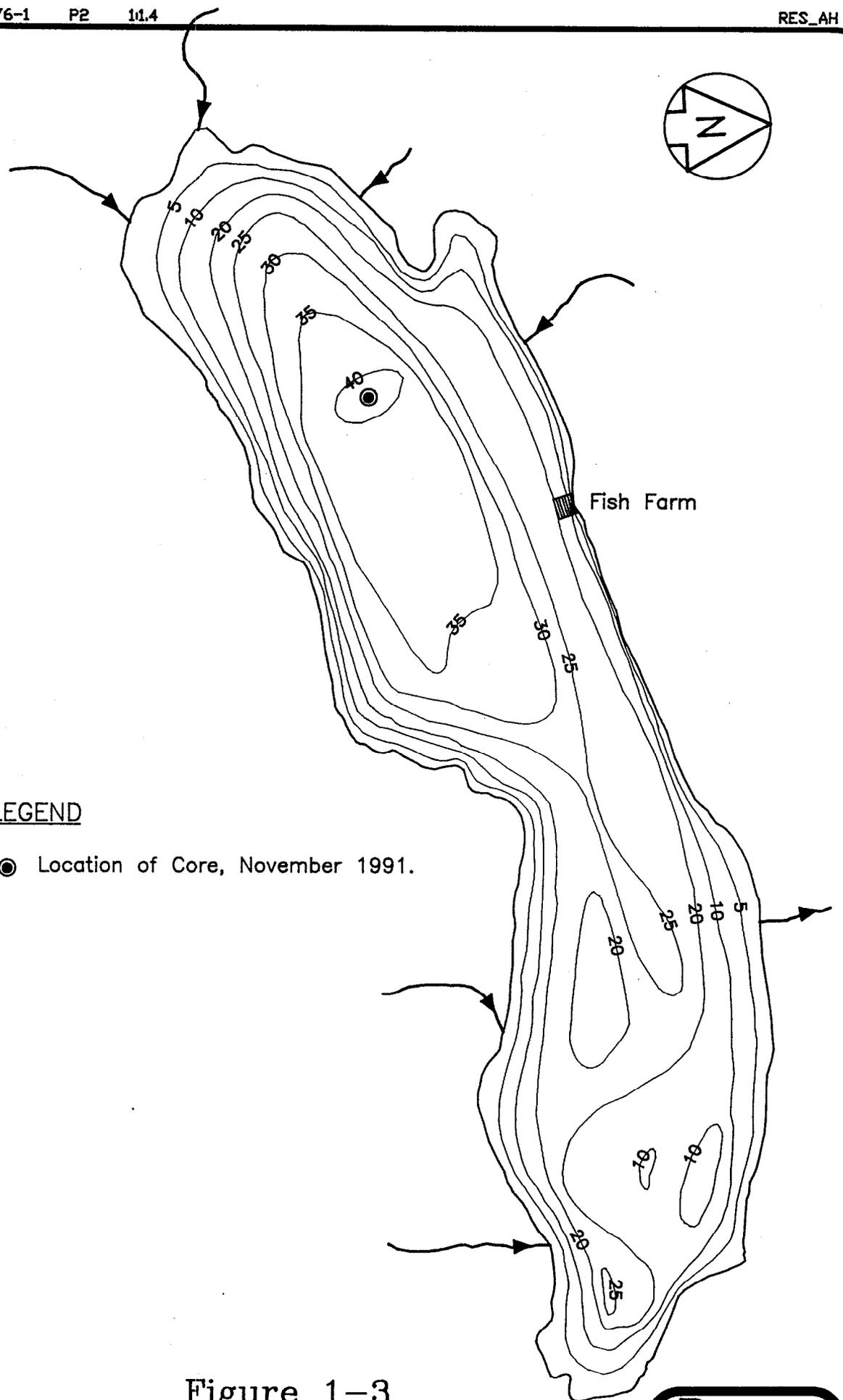
LEGEND

⊙ Location of Core, November 1991.

Fish Farm

Figure 1-3
Keogh Lake Sampling Station

questionable, however, given that only two trout in each lake were examined. A dissolved Zn concentration of 60 µg L-1 was measured in lake water in February 1971.

Ten months after mining ceased, the clarity of the lake water had improved, although metal concentrations in the water and fish tissue had not changed (Hallam *et al.* 1974).

Sampling of benthic surface sediments by Rescan in September, 1990 (Rescan 1991) indicated that tailings are widespread in Benson Lake, and are being progressively covered with organic-rich deposits. Sequential extraction studies suggested that chemical reactivity of the tailings on the lake floor was minimal (Rescan 1991). Water quality measurements indicated that the chemistry of the lake waters was very similar overall to that in Keogh Lake, with the exceptions of alkalinity, conductivity, and total dissolved solids which were all higher in Benson but matched levels in the inflow waters to the lake (Rescan 1991). Keogh Lake water had higher concentrations of phosphorus, chlorophyll *a*, and total organic carbon indicating higher productivity in this basin which may be partially attributed to the resident fish farm at Keogh Lake. Deep waters in both basins below a depth of about 35 m were notably depleted in dissolved oxygen in September 1990, exhibiting concentrations near the bottom of about 3 mg L-1 (~30% saturation).

Net-phytoplankton densities and community structure in Benson Lake were similar to those found in both Keogh Lake and other B.C. mountain lakes. Zooplankton densities were significantly lower in Benson than in other oligotrophic coast lakes, but were similar to those in Keogh. Aquatic vegetation was well established in the littoral zone of Benson Lake, but contained higher concentrations of Cu and As than in Three Isle Lake (Rescan 1991; Figure 1-1). Dissolved copper levels were similar in both basins, ranging from <1 to 3 µg L-1 and closely bracketing the B.C MOE and CCREM guideline of 2 mg L-1. Concentrations of metals in the flesh and livers of fish in both lakes were within the range established for fish resident in unpolluted Canadian waters. Studies of stomach contents suggested that the fish in Benson Lake were incorporating the re-established benthic invertebrate community in their diet.

In summary, the preliminary work (Rescan 1991) suggested that 17 years after the cessation of tailings discharge the tailings on the lake floor are not degrading the biochemical environment of Benson Lake.

1.2 Acknowledgements

The financial assistance provided by Placer Dome Inc. and the many useful discussions with Jim Robertson of Placer Dome Inc. are greatly appreciated. In additon, many individuals have contributed to this project. Clem Pelletier of Rescan Environmental Services (Rescan) provided project coordination and senior review of the report, as well as contributing in the field. Dr. Tom Pedersen of the University of British Columbia (Oceanography Dept.) was responsible for detailed sediment and interstitial water work, including sampling, analysis and reporting.

2.0 METHODS

In order to retain sample integrity, core sampling and processing methods required that due attention be afforded to the absolute exclusion of oxygen following sample collection. The details of core collection and processing are described in this section in conjunction with the solid-phase and interstitial chemical analyses.

2.1 Core Collection and Processing

Cores, 8.8 cm in outside diameter, were collected from both lakes using butyrate tubes and a lightweight stainless-steel catcher- and cutter-free gravity corer (Pedersen *et al.* 1985). The quality of the cores obtained was very good. The clear supernatant water on recovery indicated that little disturbance of the interface had occurred during coring. Cores were sealed with a full column of supernatant water immediately after removal from the corer, logged, and transported hand-held to shore. Detailed core logs are listed in Appendix A.

Interstitial water samples were extracted from the cores beside both lakes, using a van as a portable laboratory. 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 core barrel. The supernatant water on the top of the core was carefully 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), with electrical power being supplied by a generator. 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^{TM} Syrfil 0.45 μm cellulose ester 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. An aliquot of most 0.45 μm-filtered samples was subsequently refiltered through 0.1 μm Nuclepore^{TM} polycarbonate membranes, in order to permit assessment of the proportion of "colloidal" metals present in the pore waters. Ultrapure Seastar$^{®}$ concentrated HNO_3 was then added 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 DDW (distilled, deionized water); 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® 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, one cm increments were used for the next several cm, and 3 or 4 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 stored frozen and subsequently 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.

3.0 RESULTS

The core processing results from Benson and Keogh Lakes are outlined below. Both major and minor element concentrations in the solid-phase of each core are discussed with particular attention given to Cu, Cd, Fe, Mn, Pb and Zn solid-phase concentrations. The interstitial water chemistry, in conjunction with the solid-phase analyses, provides a complete *snapshot* of sediment reactivity. The large volume of data collectied for each of these cores has been summarized graphically; however, the reader must be referred to Appendix C and D for detailed examination of core data.

3.1 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. Organic carbon (C_{org}) , nitrogen and sulphur were measured using Carlo-Erba elemental analyzers, while carbonate carbon was determined by coulometry. All data are listed in Appendix C.

Organic carbon and nitrogen contents in the upper three decimetres of the Benson Lake sediment column are on the order of 7 and 0.3 wt. % respectively (Figure 3-1). At depths greater than ~30 cm concentrations of both parameters fall by an order of magnitude. These pronounced declines, coupled with the presence of high copper (Figure 3-2), sulphur and iron contents (Figure 3-3) below the 30 cm depth horizon, reflect the presence of buried organic-poor but copper- and pyrite-rich tailings at depth in the core.

In contrast to the upper stratum overlying the tailings in the Benson core, natural sediments from the central basin of Keogh Lake exhibit significantly higher C_{org} and nitrogen levels: organic carbon contents range up to 23 wt. % (Figure 3-1). Copper levels are enriched in the upper 6 cm of the deposits, reaching concentrations up to 200 μg g-1, some three times higher than Cu contents observed at depth (Figure 3-2). Organic carbon and sulphur distributions parallel each other in the core (Figure 3-3), suggesting that the sulphur in the deposits is mostly of organic origin. The two parameters are approximately linearly correlated ($r = 0.61$) and a scatter plot of organic C versus total S (Figure 3-4)
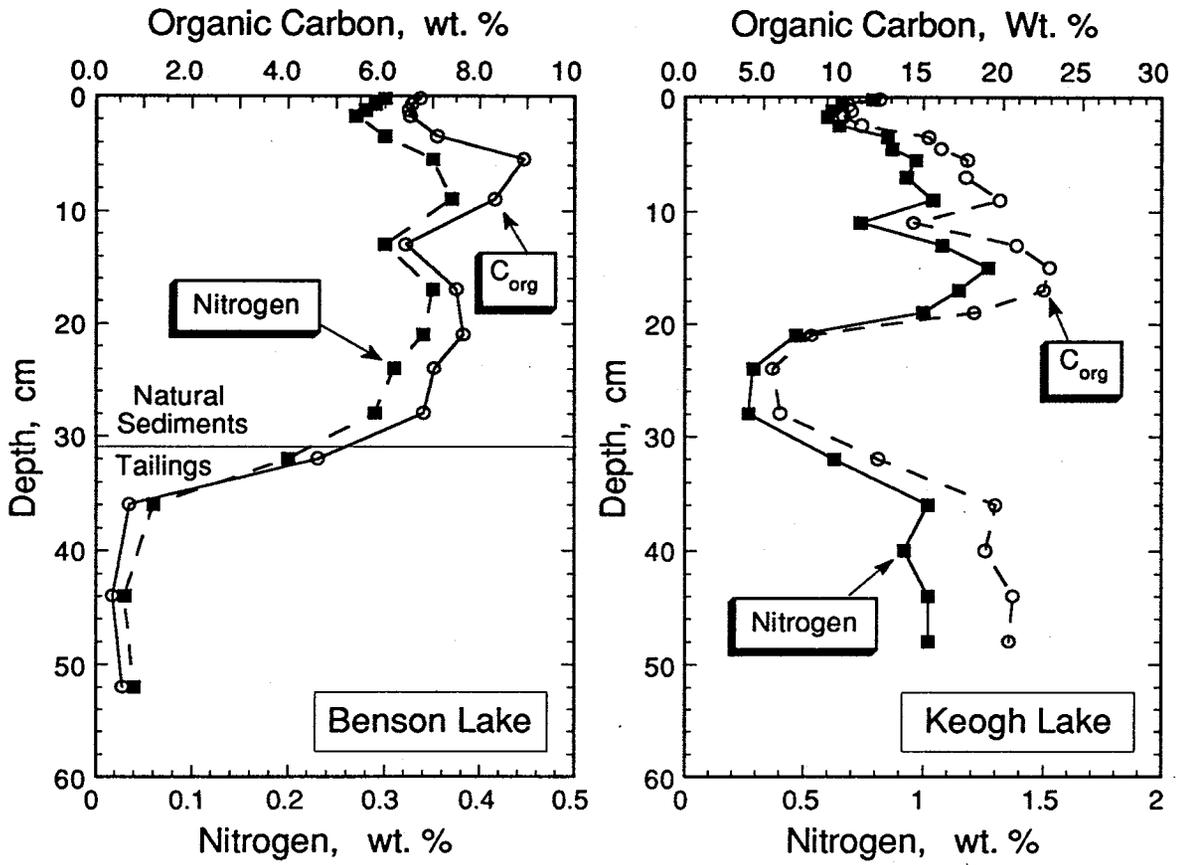
Figure 3-1: Organic Carbon and Nitrogen Distributions in Benson and Keogh Lake Sediments
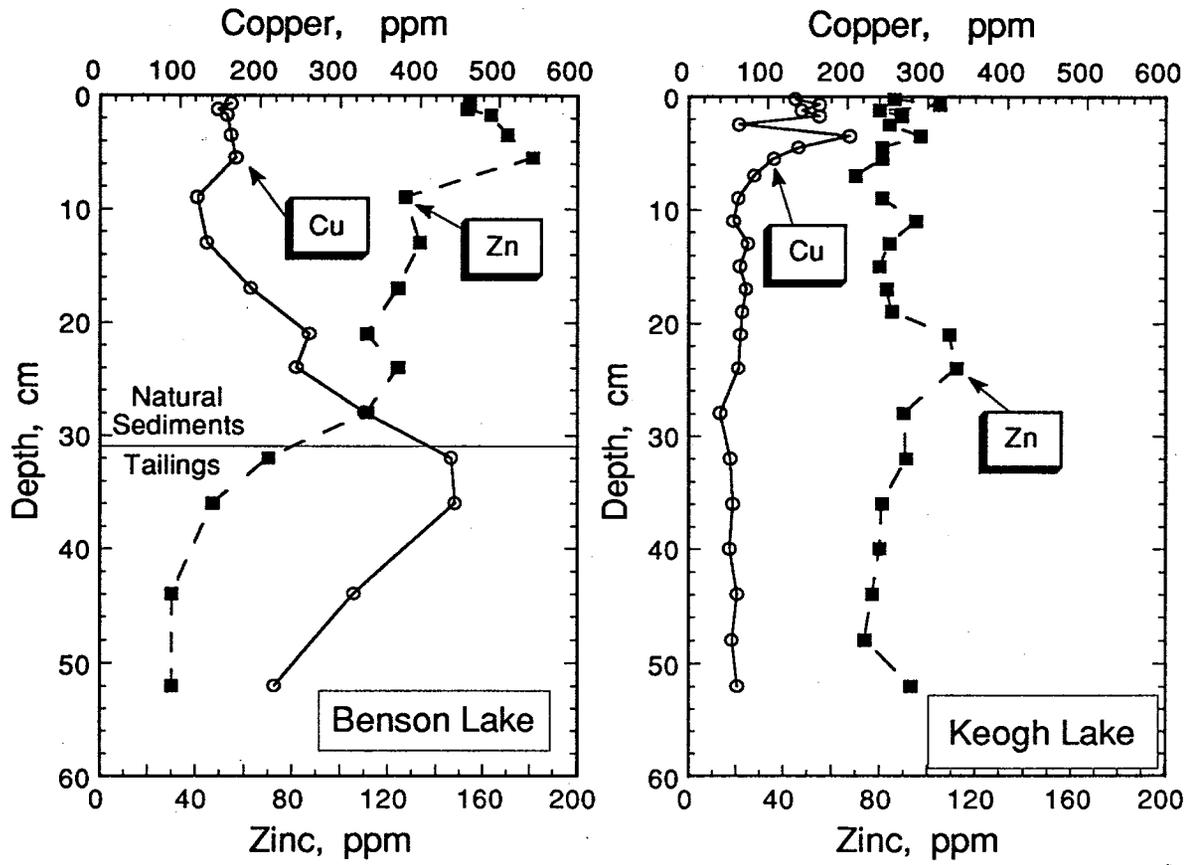
Figure 3-2: Distribution of Solid-Phase Copper in Benson and Keogh Lake Sediments
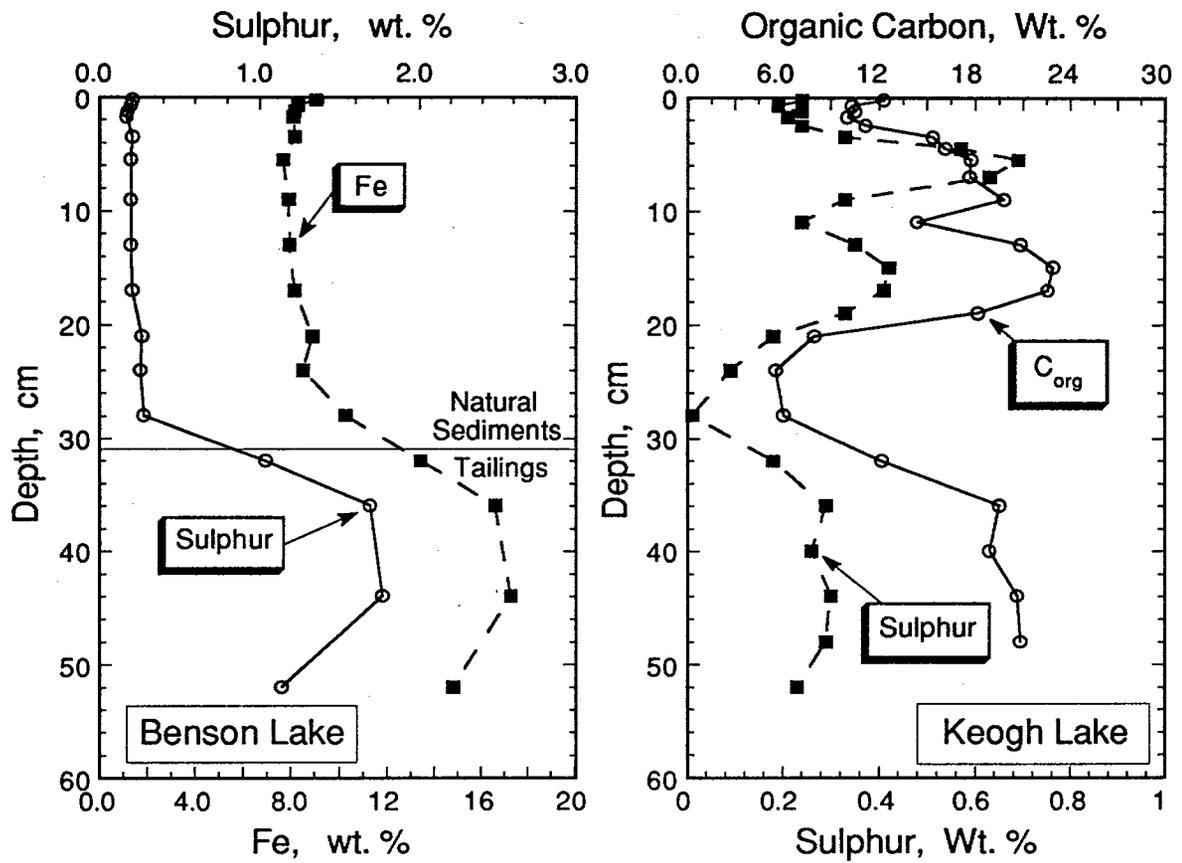
Figure 3-3: Sulphur, Iron and Organic Carbon Distributions in Benson and Keogh Lake Sediments
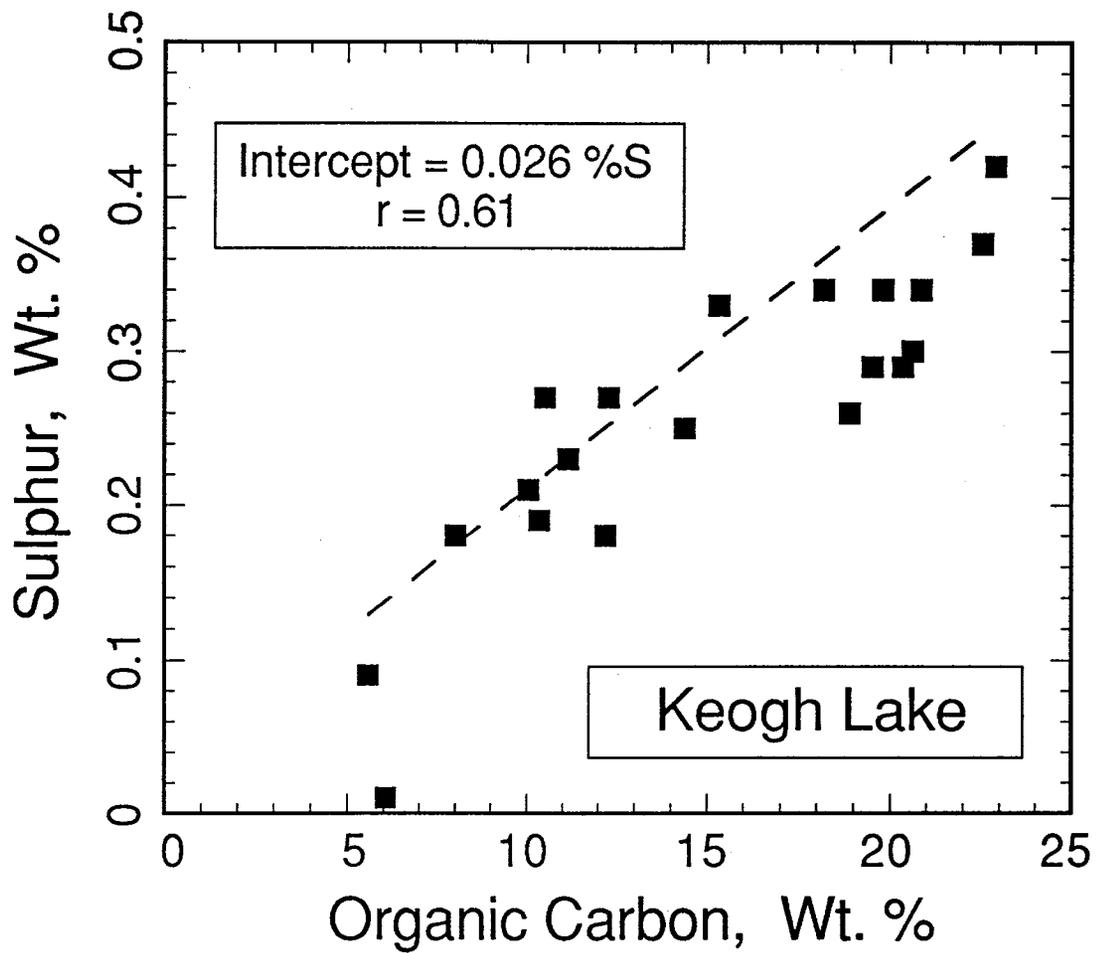
Figure 3-4: Organic Carbon and Sulphur Correlation in Keogh Lake

yields an intercept of 0.026 % S, indicating that there can be little sulphide-sulphur present in the deposits.

Major element:Al weight-ratio data indicate that the tailings are relatively enriched in Si, Ca and Mg (Figures 3-5, 3-6 and 3-7). They are not compositionally homogeneous however, as indicated by slight variations in the elemental ratios below 35 cm depth. Previous petrologic study of a single sample of "land tailings" indicated abundant quartz, amphibole and calc silicate minerals indicative of a skarn-type deposit. This assemblage explains the Si, Ca and Mg distributions seen in the tailings stratum of the core. The data also indicate that sodic feldspars, and potassium-bearing orthoclase and biotite are not common in these deposits. Carbonate is present in the tailings stratum but the contents are low, reaching a maximum of about 5 wt. % at 36 cm depth (Appendix C). Major element:Al weight ratios in the Keogh deposits are significantly lower than in the upper half of the Benson Lake core (Figures 3-5 to 3-7; Appendix C). This contrast indicates that the Keogh sediments are finer-grained than those in the central basin of Benson Lake, because fine-grained clays are relatively rich in Al compared to the coarser-grained quartzo-feldspathic fraction. This conclusion is consistent with X-ray diffractometry data reported previously (Rescan, 1991). A generally finer texture would be expected in the Keogh deposits, given that fluvial detritus is delivered to the lake via a series of small creeks; Benson Lake is supplied with (presumably coarser) fluvial debris via the larger and swifter Raging and Benson rivers.

Fe/Al and Mn/Al profiles in both lakes indicate that iron and manganese are enriched relative to the aluminosilicate fraction in surface or near-surface deposits (Figure 3-8). Such profiles are common in lakes (see the review in Rescan, 1989) and can be attributed to the preferential accumulation of iron and manganese oxyhydroxide phases near the sediment-water interface. Such accumulation of "excess" Fe and Mn appears to be particularly profound in the top 5 mm of the Keogh deposits (Figure 3-8).

Relative to "natural" sediments in the Benson Lake, the buried tailings are significantly depleted in Zn ($\sim$30-40 μg g^{-1}; Figure 3-2), Pb ($<$5 mg g^{-1}; Figure 3-9), Cr and Ba ($\sim$70 and $\sim$50 μg g^{-1}, respectively; Figure 3-10), and Rb and Zr ($<$10 and $\sim$50 μg g^{-1}, respectively; Figure 3-11). The term "natural" may be a misnomer considering that the copper content in the upper stratum of the Benson deposits is higher than that typically observed in unpolluted lacustrine sediments, such as those at depth in Keogh Lake (Figure 3-2). Previous work in Benson Lake (Rescan, 1991) showed that very fresh,
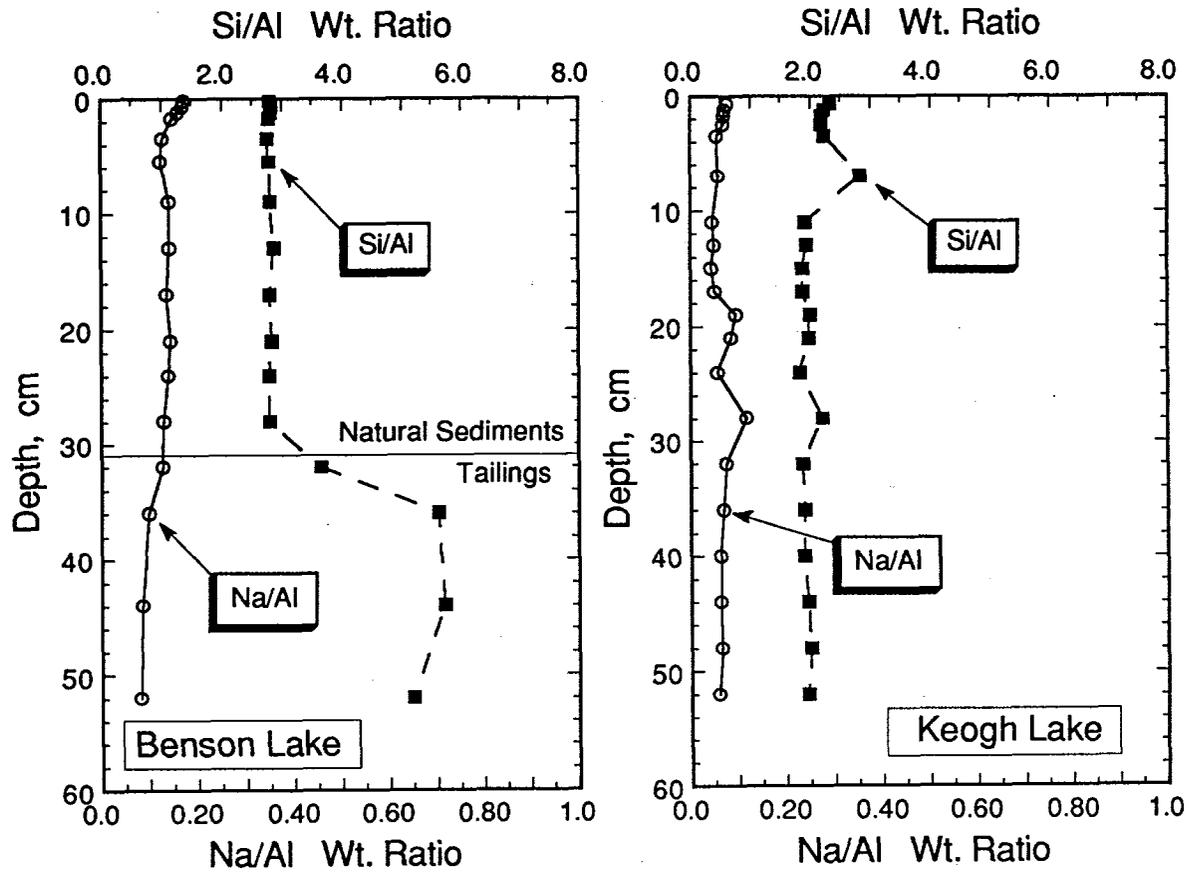
Figure 3-5: Si, Na:Al Weight Ratios for Benson and Keogh Lake Sediments
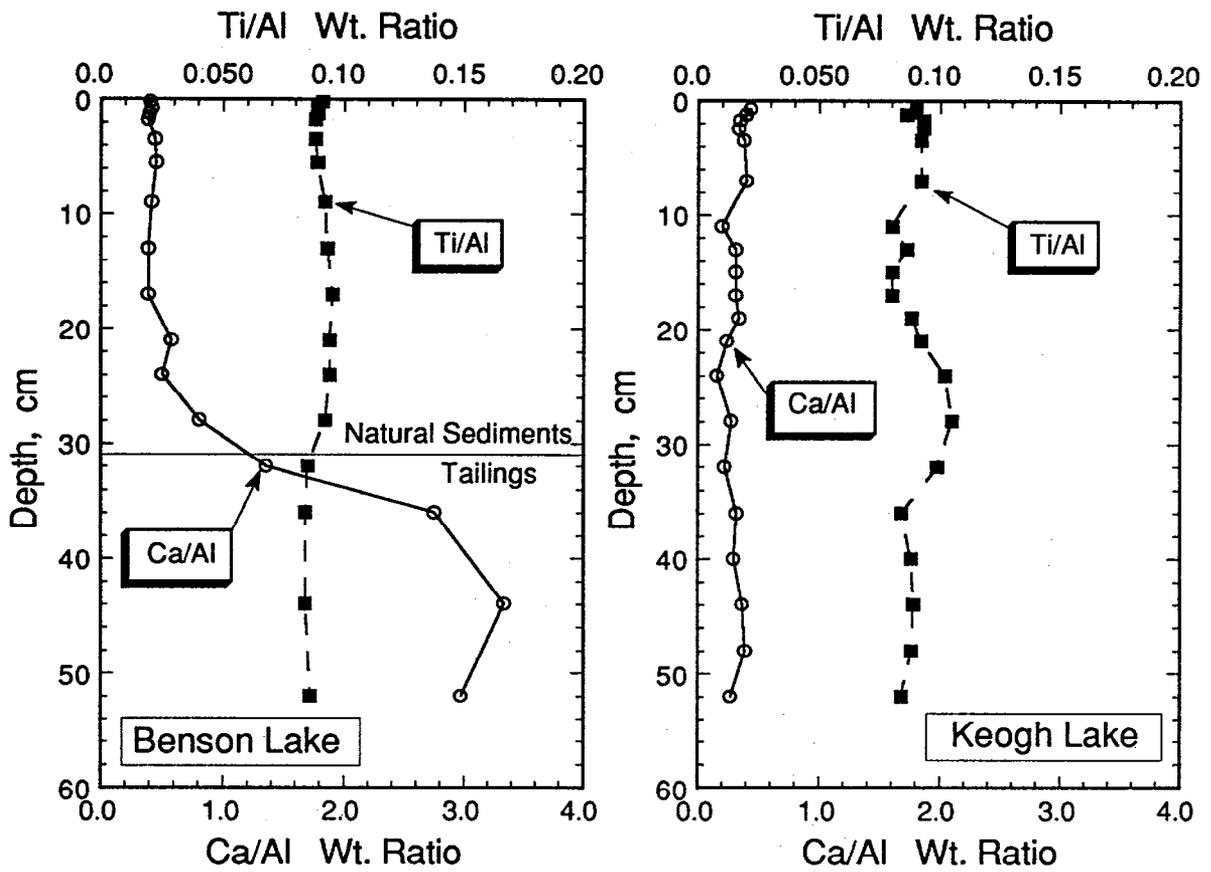
Figure 3-6: Ti, Ca:Al Weight Ratios for Benson and Keogh Lake Sediments
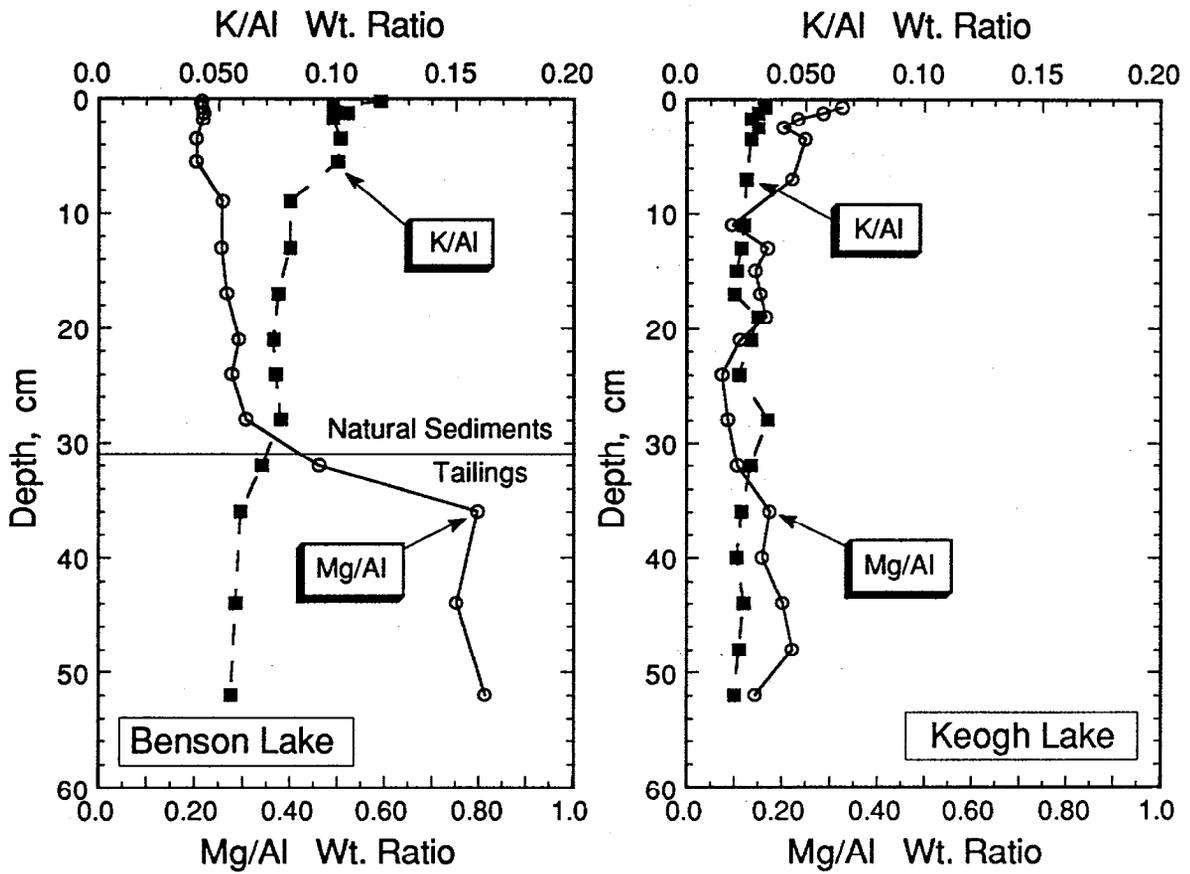
Figure 3-7:   K, Mg:Al Weight Ratios for Benson and Keogh Lake Sediments
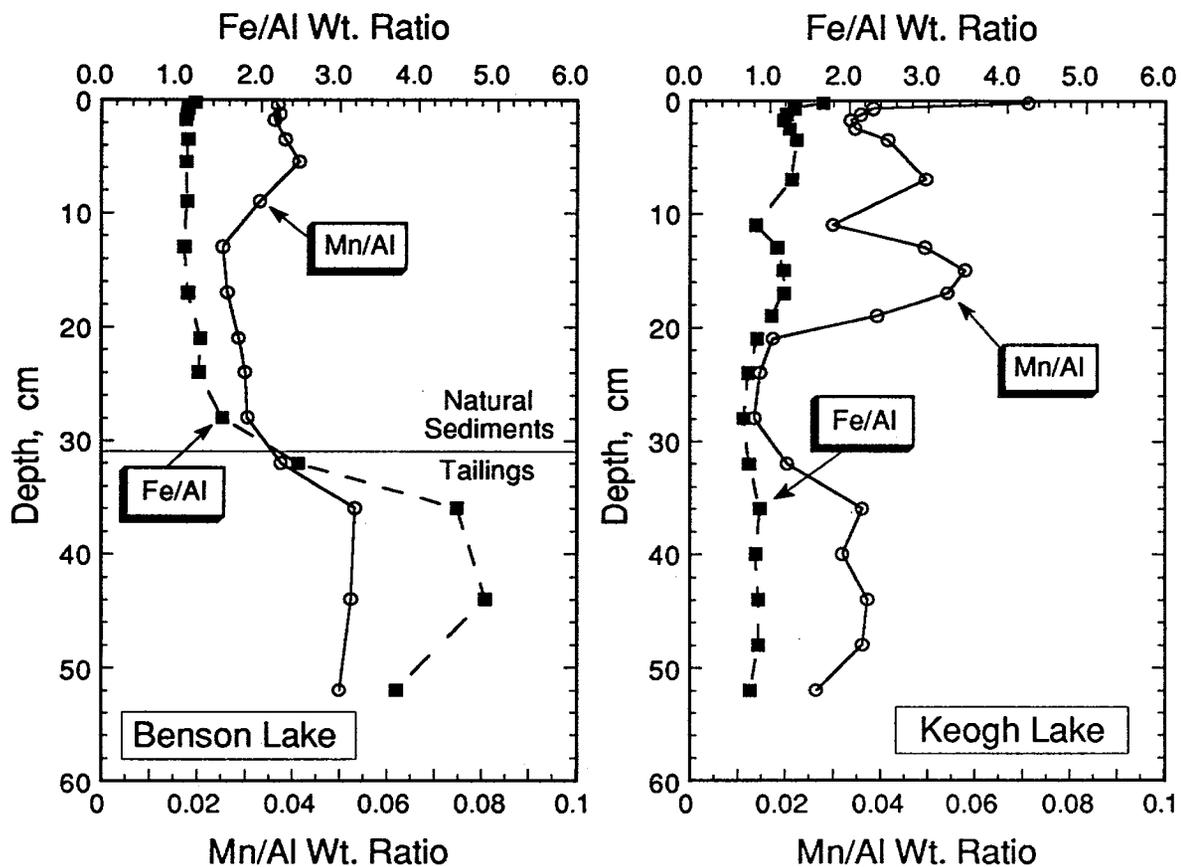
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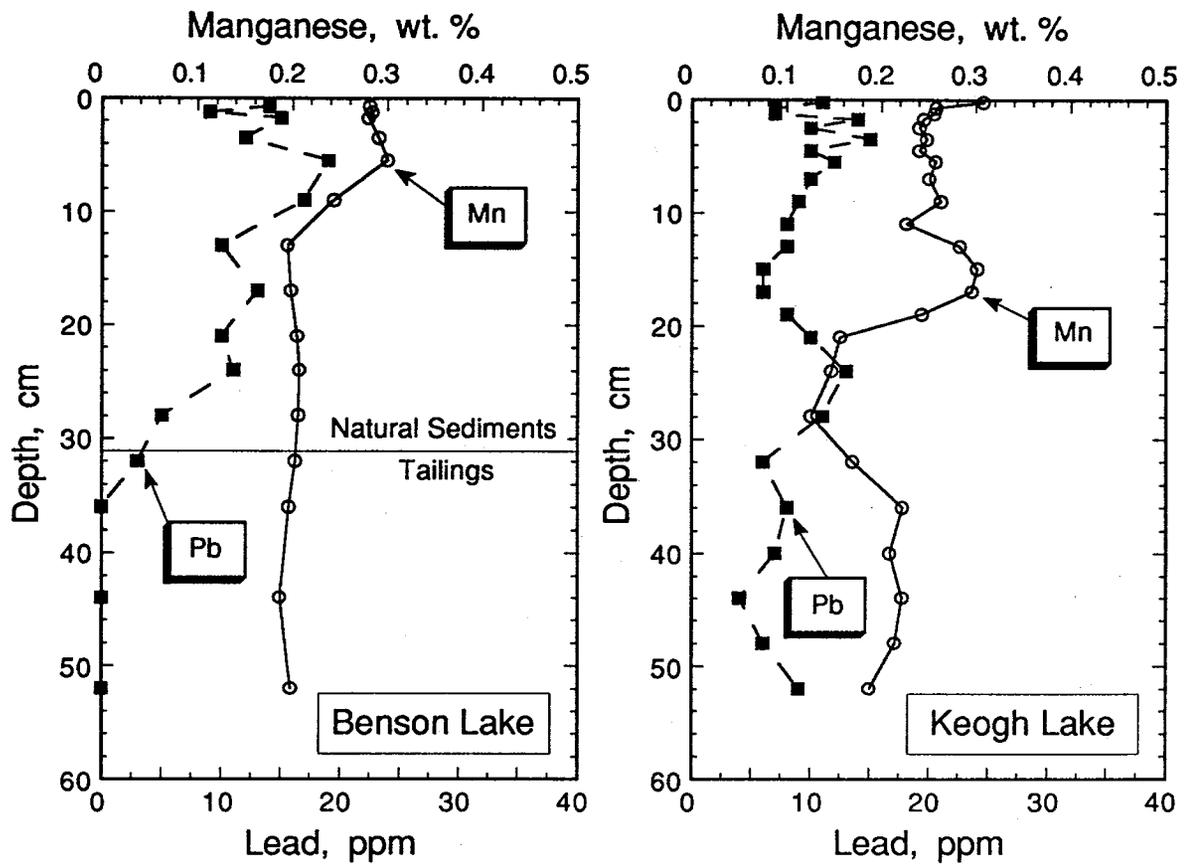
Figure 3-9: Solid-Phase Mn and Pb Distributions in Benson and Keogh Lake Sediments
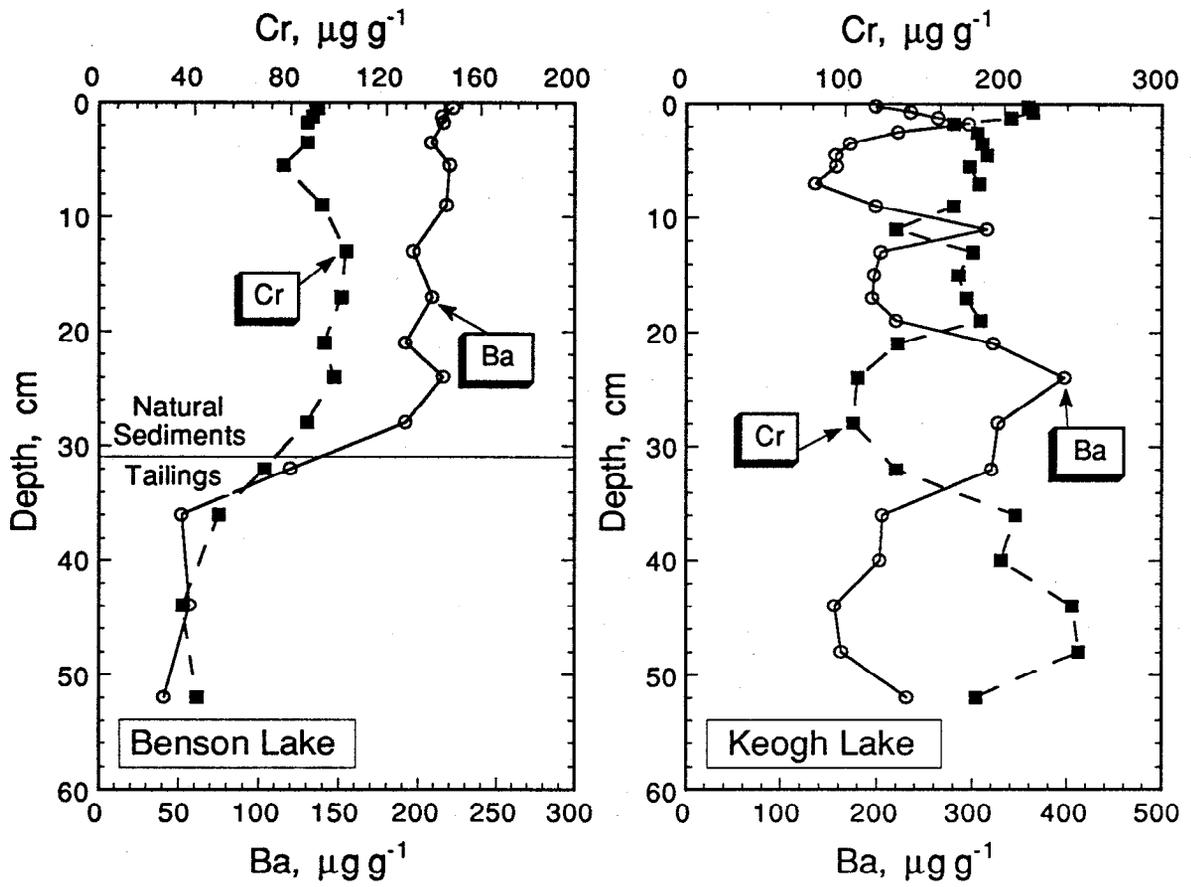
Figure 3-10:   Solid-Phase Cr and Ba Distributions in Benson and Keogh Lake Sediments
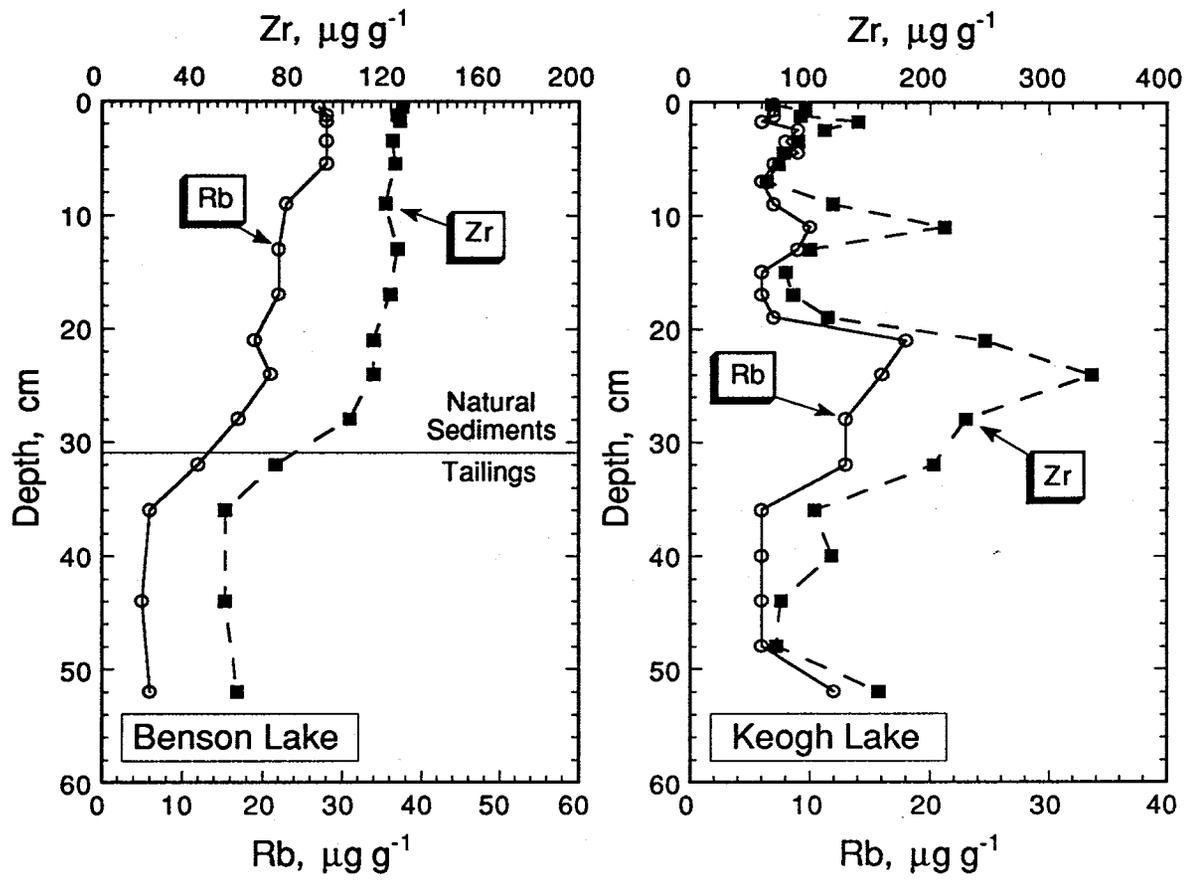
Figure 3-11: Solid-Phase Zn and Rb Distributions in Benson and Keogh Lake Sediments

unoxidized chalcopyrite particles are a ubiquitous trace constituent in surface sediments, despite the passing of 16 years since deposition ceased. It is not clear whether the origin of such particles is from bioturbation, or from continuing but waning redistribution of submerged tailings deposits. Subaerial tailings and waste rock dumps adjacent to the lake are highly weathered and can not be the source of the fresh chalcopyrite in the lacustrine sediments.

Nickel and cobalt concentrations vary little between the tailings and overlying deposits in the Benson Lake core: Ni is slightly depleted in the tailings while Co is slightly enriched (Figure 3-12). In contrast, both elements are slightly enriched in the upper several centimetres of sediments in Keogh Lake, and in a discrete horizon between 10 and ~20 cm depth, where the Co content reaches nearly 100 $\mu g\ g^{-1}$ (Figure 3-12). Immediately below this horizon, between ~20 and 30 cm depth, the deposits are depleted in organic matter (Figure 3-1), Mn and Cr (Figures 3-9 and 3-10), and enriched in Pb, Zn, Ba, Rb and Zr (Figures 3-2 and 3-9 to 3-11). This chemically-distinct stratum corresponds to the light-coloured, fine-grained band in that depth interval noted in the core log (Appendix A). This layer was intersected in two cores from the central basin of the lake, and apparently resulted from a single episode of deposition of very fine-grained detritus having an anomalous mineralogic composition. A flood event or a slump into one of the creeks in the watershed could potentially explain this feature. Clearly, the sediments in Keogh Lake are not compositionally homogeneous with depth.

3.2   Interstitial Water Chemistry

Pore waters were filtered through both 0.45 μm and 0.1 μm filters and analyzed for dissolved Zn, Cu, Pb, Cd, Fe, and Mn. Sulphate was determined only on the <0.45 μm filtrate. Analytical methods and quality control measures are described in Appendix B, and all concentration data are listed in Appendix D. In some cases insufficient sample was recovered to permit filtering of an aliquot through a 0.1 μm filter or for some horizons, the size of the <0.1 μm sample was too small to permit analysis of all six metals; these are noted in the data tables. Concentrations measured in some 0.1 μm-filtered aliquots were higher than those in the parent 0.45-filtered samples and were therefore believed to be contaminated. This is particularly true for Zn, and to some extent Cd, in the <0.1 μm subsamples analyzed in the Keogh Lake study. These data were therefore rejected, and noted as being contaminated in Appendix D. Several samples from the Benson Lake <0.1 μm sample suite also were apparently   contaminated   with   Zn,   but   not   Cd.   The   source

of the contamination was probably the disposable filter discs, although these had been acid-washed and rinsed with high -purity water prior to use. Why these filters appear to have contaminated only some samples with zinc and cadmium is not clear.

Dissolved Fe and Mn profiles in both size fractions are shown in Figures 3-13 and 3 -14. Concentrations of 1.16 and 0.37 mg L-1 Fe and 0.44 and 0.19 mg L-1 Mn were measured in the <0.45 µm supernatant water samples from Benson and Keogh lakes, respectively. These levels are of the same order as those measured September, 1990 by Rescan (1991) one metre above the bottom at the same sites (Table 3-1), and are roughly two orders of magnitude higher than concentrations measured higher in the water columns of both basins (see the data in Tables B-2 and B-4 of Rescan, 1991). The concentrations of both iron and manganese increase sharply at shallow depths in the pore waters of both lakes. Dissolved Fe levels reach nearly 80 mg L-1 in the upper decimetre of Benson Lake sediments and 60 mg L-1 within 3 cm of the interface in the Keogh Lake core (Figure 3-13). Interstitial manganese contents are lower, reaching similar maxima of ~18 mg L-1 at 5.5 cm depth in the Benson Lake deposits and 1.25 cm in Keogh sediments. Concentrations of both elements decline roughly exponentially at depth in both cores, with the decrease being particularly marked in the Keogh deposits. Nearly 100% of the dissolved Fe in the <0.45 µm fraction in the Benson Lake pore water samples passed the 0.1 mm filter (Figure 3-13). Although the same observation applies to the samples below 5 cm depth in the Keogh sediments, only 10-50% of the "dissolved" iron passes a 0.1 µm filter in the upper five centimetres of the deposits. Approximately one-third of the dissolved Mn in the <0.45 µm filtrate in Benson Lake pore waters passed the 0.1 µm filter, while closer to two-thirds passed the same pore size on average in the Keogh samples (Figure 3-14).

Dissolved Zn values in the supernatant waters in both lakes (Fig. 3-15) are very similar (Table 3-1), being about 8 and 9 µg L-1 respectively in Keogh and Benson. Concentrations in the pore waters are significantly lower, invariably being less than 2 µg L-1 (Figure 3-15) in both basins, even in the upper 5 mm of the deposits. The Zn levels measured in the <0.1 µm fraction in Benson Lake are probably unreliable given the apparent contamination problem discussed above. However, if the lower values are representative, then a very high proportion of the total dissolved zinc appears to be present in true solution in the pore water, rather than occurring in a colloidal fraction.
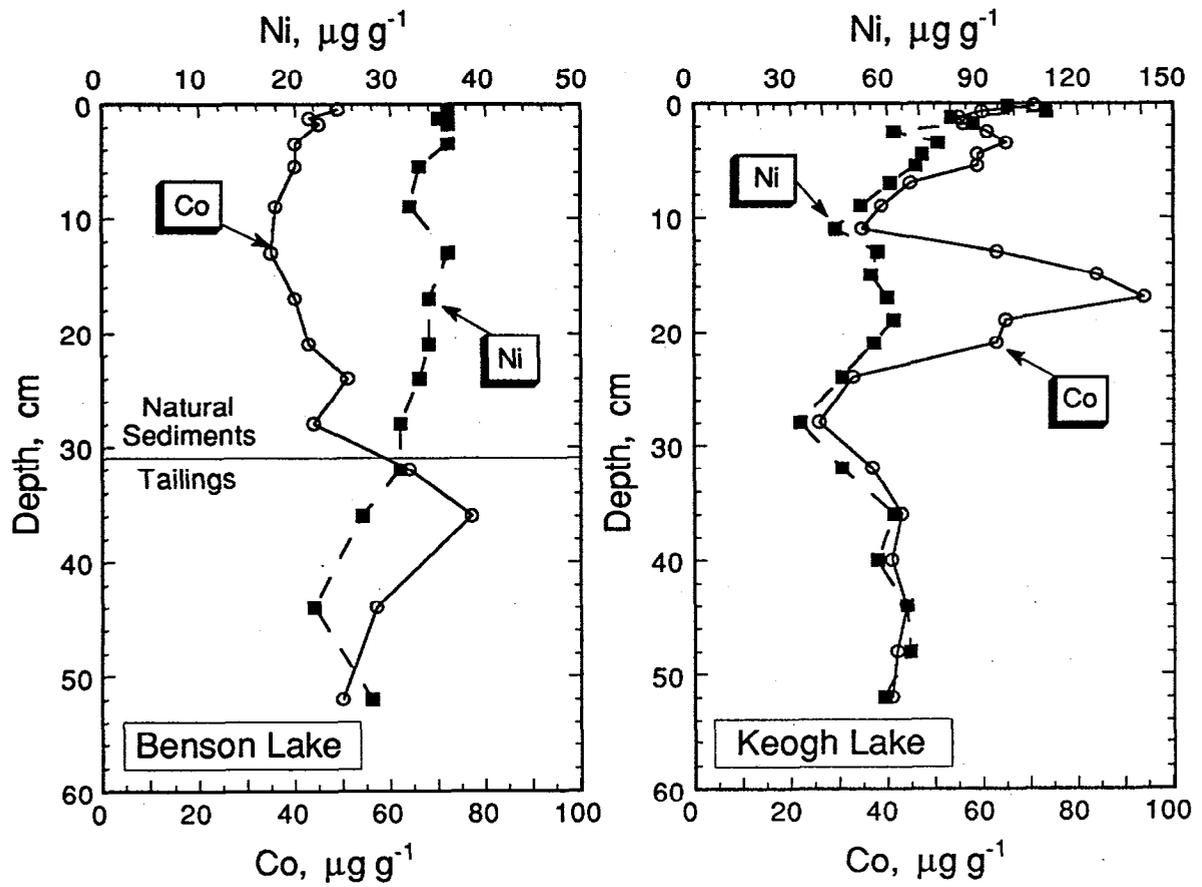
Figure 3-12: Solid-Phase Ni and Co Distributions in Benson and Keogh Lake Sediments
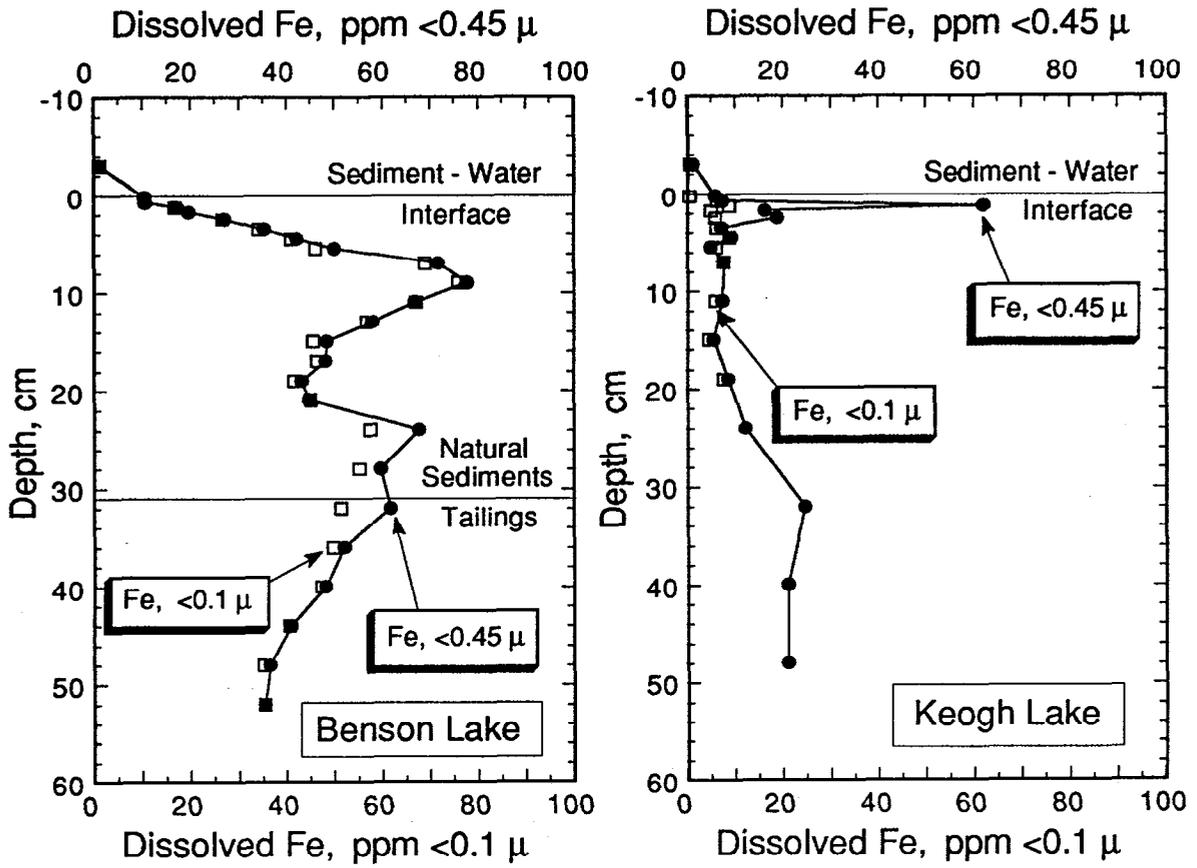
Figure 3-13: Dissolved Fe Distributions in Benson and Keogh Lake Sediments
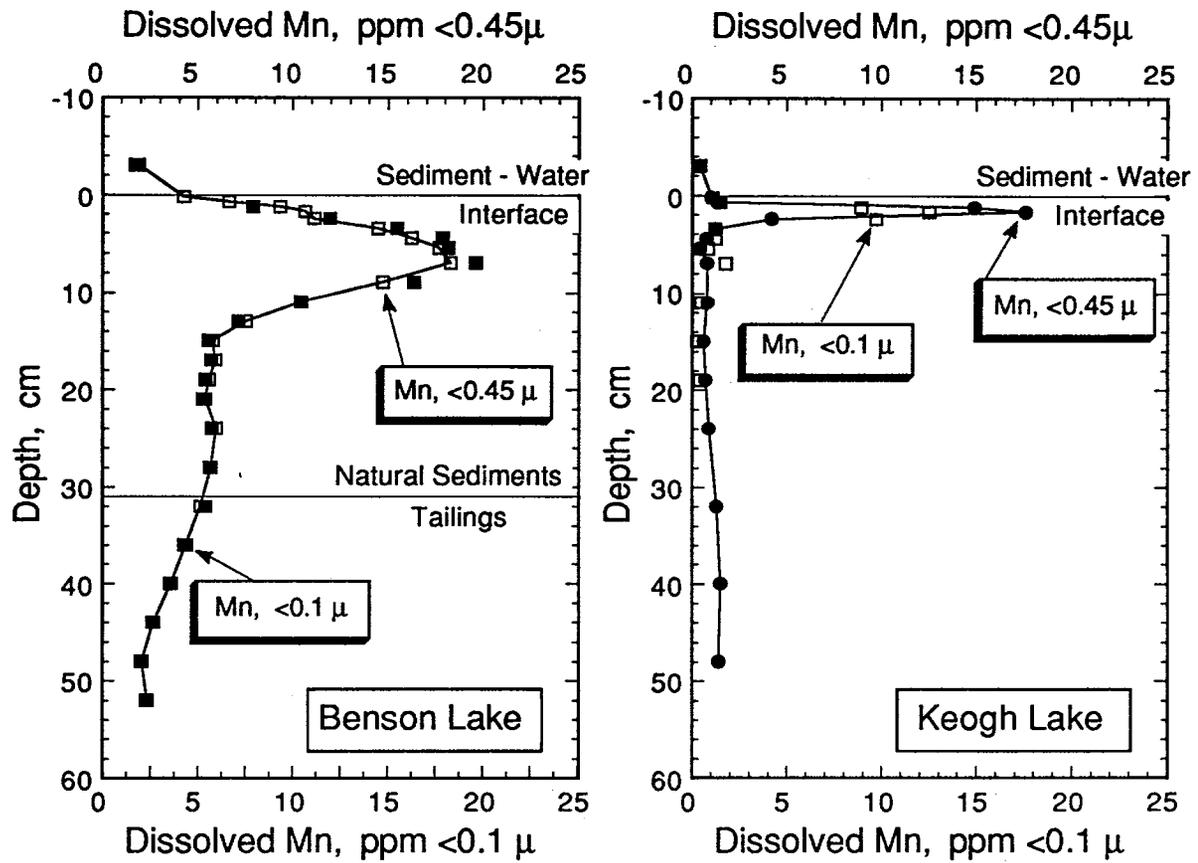
Figure 3-14: Dissolved Mn Distributions in Benson and Keogh Lake Sediments
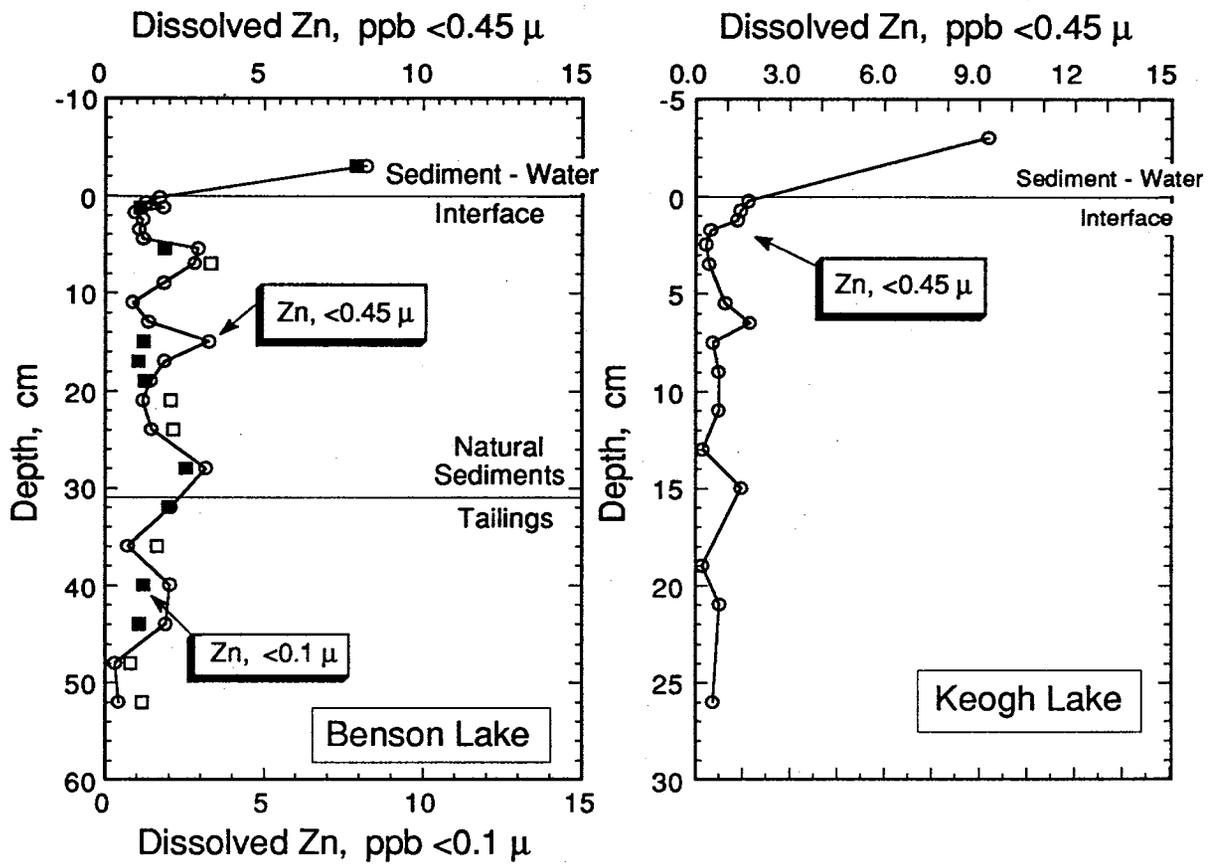
Figure 3-15: Dissolved Zn Distributions in Benson and Keogh Lake Sediments

Table 3-1

Dissolved Metal and Sulphate Concentrations in Benson and Keogh Lake Bottom and Supernatant Waters, Collected Respectively in September, 1990 and August 1991

Sample	Mn mg L-1	Fe mg L-1	Cu µg L-1	Zn µg L-1	Cd µg L-1	Pb µg L-1	SO_4^{2-} µmol L-1
Benson Bottom Water[1]	0.351	0.215	<1	<5	<0.2	<1	<10
Benson Supernatant[2]	0.435	1.16	1.52	9.3	0.56	0.52	9.6
Keogh Bottom Water[1]	0.072	0.309	2	<5	<0.2	<1	15
Keogh Supernatant[2]	0.190	0.374	1.34	8.22	0.07	1.18	6.8

1   Collected Sept. 13, 1990 by Rescan one metre above the bottom with a Go-Flo bottle at the same site as the core described in this study. Data from Rescan (1991).

2   This study. Core-top water collected by syringe under a nitrogen atmosphere and immediately filtered through a 0.45 mm filter. The samples were collected approximately 20 cm above the sediment-water interface.

Dissolved Cu concentrations in the supernatant waters at both core sites are on the order of 1.5 µg L-1 (Figure 3-16), similar to levels measured in the water columns of both lakes in September, 1990 (Rescan, 1991). In the Benson Lake core, dissolved Cu values in the upper several centimetres are very similar to that in the overlying bottom water, being ~1 µg L-1. However, below the top decimetre concentrations progressively rise, reaching a maximum of about 26 µg L-1 in the interval between about 25 and 35 cm depth, which brackets the boundary between the buried tailings and the overlying "natural" deposits. Average dissolved Cu levels in the Keogh sediments are similar to those observed in the "natural" deposits in Benson Lake, being typically 2 µg L-1. Concentrations in the upper centimetre are higher than that measured in the supernatant sample, reaching a maximum for the core of ~4 µg L-1 at 0.75 cm depth. Values generally decline with depth below this near-surface horizon. The <0.1 µm dissolved Cu data suggest that roughly 50 to 80 % of the "dissolved" copper in the <0.45 µm fraction in the Benson Lake core is present in a form that will not pass a 0.1 µm filter. In contrast, less than about 25% of the <0.45 µm copper in the Keogh sediments is retained by a 0.1 µm filter (Figure 3-16).

Pb levels in supernatant waters are about 1 µg L-1 in Benson Lake and about half that level in Keogh (Figure 3-17). As is the case for zinc, concentrations are significantly lower in the pore waters of both cores, with the exception of a subsurface maximum of
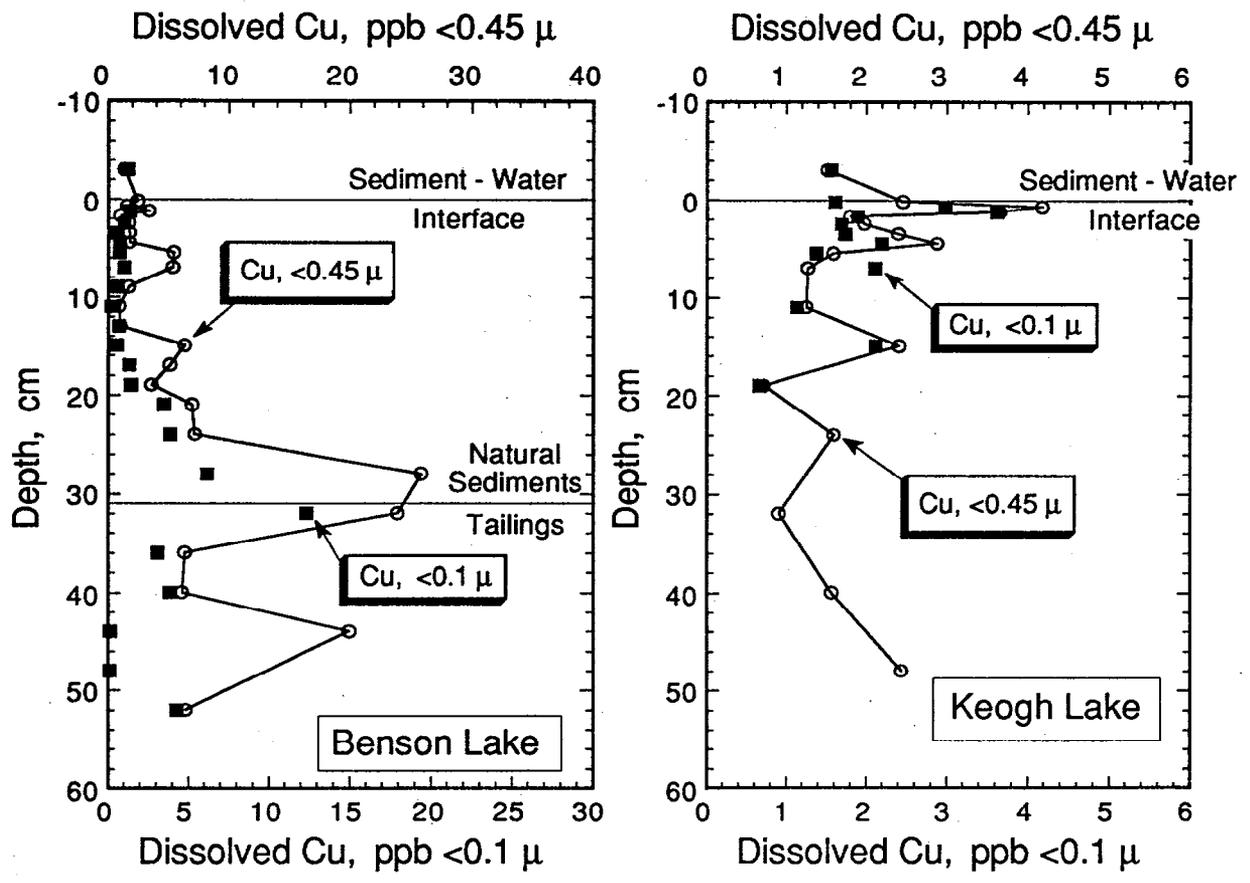
Figure 3-16: Dissolved Cu Distributions in Benson and
Keogh Lake Sediments
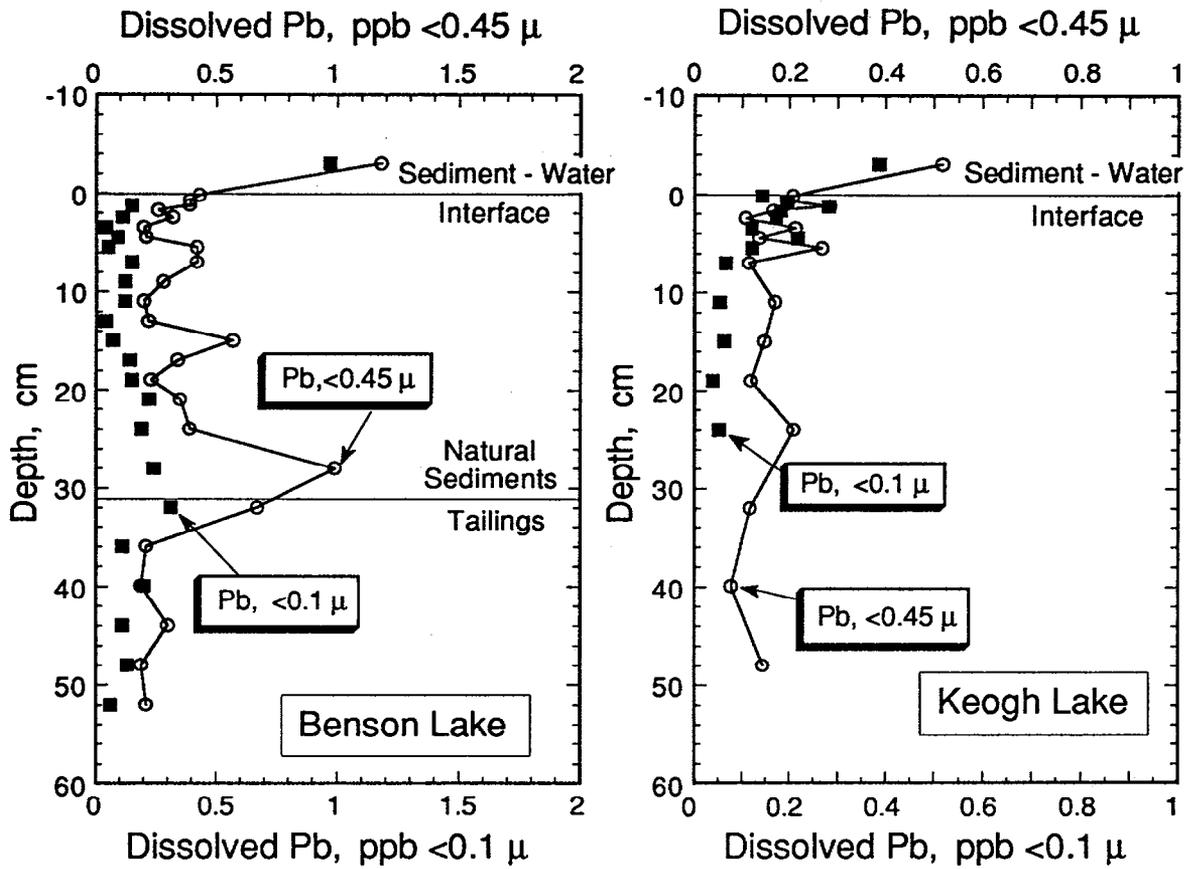
Figure 3-17: Dissolved Pb Distributions in Benson and Keogh Lake Sediments

~1 μg L^{-1} in the Benson deposits just above the tailings-natural sediments boundary (Figure 3-17). Measurements made on the <0.1 μm fraction indicate that ~40-70% of the "dissolved" Pb (the <0.45 μm fraction) is retained by the smaller pore size.

Cadmium concentrations in Benson and Keogh supernatant water are respectively 0.56 and 0.07 μg L^{-1} (Table 3-1). Levels are sharply lower in the Keogh pore waters, the concentration in the top 5 mm being 0.007 μg L^{-1}, only slightly higher than the analytical detection limit (Figure 3-18). Similarly low values prevail throughout the rest of the core. The Cd concentration in the top several centimetres of the Benson Lake deposits is also substantially lower than that in the overlying supernatant, but cadmium levels throughout the rest of the core are significantly higher than those in the same filtrate fraction of the Keogh samples. Two intervals host maxima at greater depths: peak concentrations of about 0.4 μg L^{-1} occur at 7 and 28 cm, while a peak of smaller amplitude (0.015 μg L^{-1}) occurs at 15 cm depth. Maxima at the same depths can be seen in the Zn, Cu and Pb profiles of the <0.45 μm fraction; in all cases, the amplitudes of the maxima are diminished in the <0.1 μm fraction.

Sulphate contents in Benson and Keogh Lake supernatant waters are low, being ~10 and ~7 μmol L^{-1} respectively (Table 3-1). Similarly low levels were reported in bottom waters previously by Rescan (Table 3-1). SO_4^{2-} concentrations decrease rapidly with depth in both cores, reaching a near-constant value of ~1 μmol L^{-1} below 0.5 cm depth in the Benson deposits and about 3 μmol L^{-1} below 1 cm in the Keogh Lake core (Figure 3-19). These very low levels are near the detection limit of the ion chromatograph, which for this study is estimated to be 1 μmol L^{-1}.
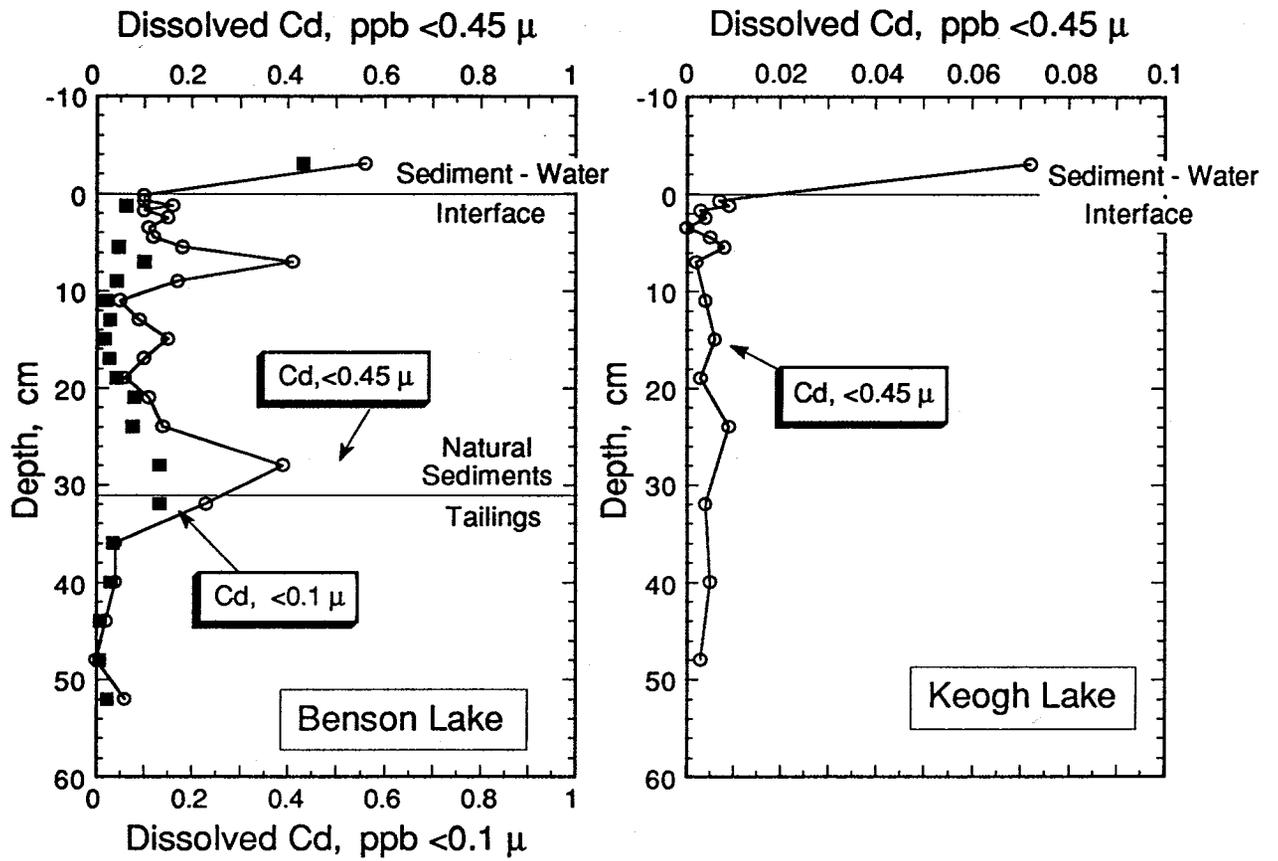
Figure 3-18: Dissolved Cd Distributions in Benson and Keogh Lake Sediments
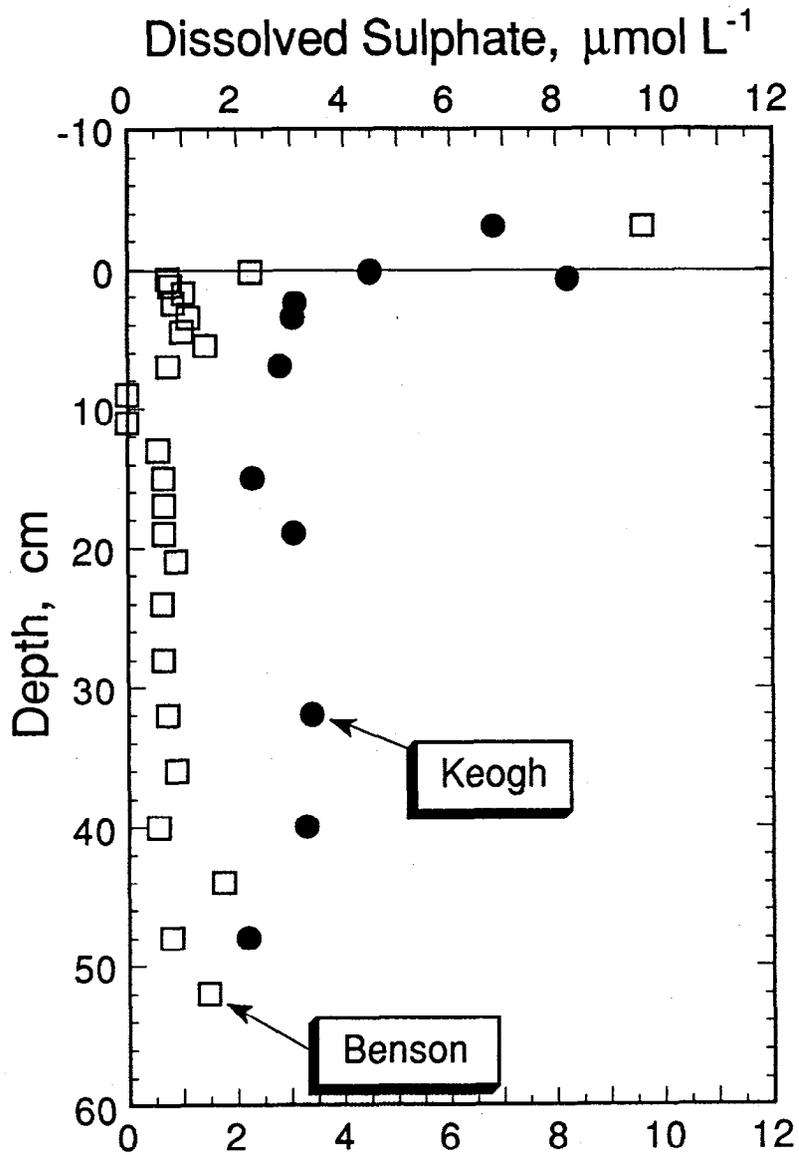
Figure 3-19: Dissolved Sulphate Distributions in Benson and Keogh Lake Sediments

4.0 DISCUSSION

4.1 Manganese and Iron Diagenesis

The degradation of organic matter in sediments proceeds via a series of overlapping, bacterially mediated electron-transfer reactions in which oxidants are sequentially consumed with increasing depth in the deposits should oxidant demand exceed supply. The sequential consumption follows the order of decreasing free energy yield. In this well known scheme, if the supply of oxygen and nitrate via downward diffusion cannot meet the demand of the sedimentary bacterial community, the O_2 and NO_3^- concentrations at some depth fall essentially to zero and Mn and Fe oxyhydroxides are utilized to oxidize organic matter (Froelich et al. 1979). The reduction contributes dissolved Mn and Fe to pore water. MnO_2 reduction occurs at a slightly higher oxidizing potential, thus at a slightly shallower depth. At the ambient pH of Benson and Keogh Lake oxic bottom waters (~7.5 and ~7 respectively in September 1990), Fe^{2+} will react very quickly with O_2 and be precipitated as FeOOH (Stumm and Morgan 1981); Fe^{2+} effectively cannot co-exist with molecular O_2 at neutral pH. Therefore kinetic effects, such as a precipitation lag, are unlikely to significantly obscure the true depth of the zero-oxygen horizon. For this reason, the level at which dissolved Fe appears in pore waters is a reasonably precise indicator of the depth of the zero oxygen boundary.

Slight increases in the Fe/Al ratio at the tops of both cores (Figure 3-8) suggests that a non-aluminosilicate phase, presumably Fe oxyhydroxide, occurs in significant quantities in the upper 5 mm. Assuming an Fe/Al ratio of 1.06 for the aluminosilicate fraction in the near-surface deposits, and using the measured Al concentrations, the "excess" iron contents are ~0.8 and ~2.4 wt. % respectively in the top 5 mm of the Benson and Keogh Lake sediments. "Excess" Mn appears to be confined to the upper 5 mm in Keogh Lake (Figure 3-8). A similar calculation using an Mn/Al ratio of 0.04 for the aluminosilicate fraction yields 0.13 wt. % "excess" or presumed oxide Mn in the top 5 mm of the Keogh sediments and 0.08 wt. % oxide Mn at the top of the Benson Lake core. The Benson Lake profile suggests that "excess" manganese is present throughout the top 6 cm of the core. The presence of oxidized iron and manganese phases in the near-surface sediments in both lakes has important implications for the diagenetic behaviour of heavy metals, given that both phases are effective at scavenging metals from solution (Balistrieri and Murray 1984; Kadko et al. 1987).

At both sites examined in this study, the occurrence at very shallow depths of dissolved Fe concentrations higher than those in the supernatant waters suggests that the sediments are anoxic or suboxic within about 1-2 cm of the interface. However, there are significant differences between the two lakes, as shown by the profiles in Figures 3-13 and 3-14. The dissolved manganese profile in the Keogh Lake core is characterized by a sharp peak centred on ~1.5 cm depth. The steep decline immediately below this depth may be attributed to precipitation of rhodochrosite ($MnCO_3$) which is a known authigenic precipitate in anoxic lacustrine pore waters of near-neutral pH (e.g. Carignan and Nriagu 1985). Close comparison of the profiles of the <0.45 and <0.1 µm fractions in the Keogh deposits suggests that the sharp peak in dissolved Fe content at ~1.5 cm may be largely due to the presence of colloidal Fe in the pore waters between 1 and 2 cm depth (Figure 3-13). Definitive conclusions regarding the near-surface diagenesis of Fe in this core and the proportion of the element in true solution are therefore difficult to make. In contrast, the relatively close correspondence between the dissolved Mn profiles in the <0.45 and <0.1 µm fractions in this core indicates true dissolution of manganese oxides in the 1-2 cm depth interval. These data support the suggestion that the Keogh deposits are anoxic at very shallow depths.

The iron and manganese distributions in Benson Lake pore waters suggest that the sediments in this basin are less reducing at shallow depths than in the Keogh deposits: maxima for both dissolved metals occur at greater depths (7 cm for Mn^{2+} and 9 cm for Fe^{2+}) and depletion below these peaks is more subdued. Concentrations are essentially identical in both filter fractions indicating that there can be little colloidal Mn or Fe in the extracted pore waters. The depletion of Mn with depth in this core can be attributed to the precipitation of $MnCO_3$ as noted above. Assuming steady state, the decline of dissolved iron from ~80 mg L-1 at 9 cm depth to ~40 mg L-1 at 50 cm depth cannot result from the precipitation of FeS because there is essentially no reducible sulphate present in the pore waters below the uppermost centimetre (Figure 3-19). Dissolved Fe is also present in great excess compared to sulphate in the lower half of the core - the "missing" 40 mg L-1 could have been precipitated as FeS only if ~700 µmol L-1 of sulphate had been reduced to sulphide. This is impossible given the paucity of sulphate in the lake. Iron solubility at depth in the Benson sediments is instead probably controlled by equilibrium with respect to $FeCO_3$ (siderite) which commonly precipitates from sedimentary pore waters rich in reduced iron but depleted in sulphate (e.g. Postma 1981 and 1982).

Compared to the Keogh profiles, the more gradual decline in Fe and Mn concentrations with depth in pore waters below the shallow maxima in the Benson core implies that diagenetic precipitation of carbonate species is thermodynamically more favoured in the Keogh deposits. This is not surprising given the comparative sedimentary organic matter contents in the two basins (Figure 3-1). The production of alkalinity-producing metabolites such as NH_4^+ would be expected to be more profound in the more organic-rich Keogh Lake sediments; this would drive up the pH, in turn encouraging the early diagenetic precipitation of carbonate minerals.

In summary, the dissolved iron and manganese data indicate that the zero-oxygen boundary in the sediments of both Benson and Keogh lakes was within 1 to 2 centimetres of the sediment-water interface at the time of sampling. We cannot determine from the these "snapshot" profiles whether or not this condition prevails throughout the year in both basins. However, given the relatively high organic matter contents of the near-surface sediments in both lakes, it is probable that the zero-oxygen boundary remains shallow during the course of the seasons. This tentative conclusion can only be confirmed by more frequent sampling.

4.2 Zinc, Copper, Lead and Cadmium Diagenesis

Measurements made previously by Rescan (Rescan 1991) indicate that dissolved (i.e. <0.45 μm) metals concentrations in the bottom waters of Benson and Keogh lakes are relatively low, being below their detection limit for Cu, Zn, Pb and Cd (Table 3-1). More sensitive measurements made in the supernatant water for this study confirm that dissolved Cu, Pb and Cd levels in bottom waters are low and similar in both basins. Zn concentrations are significantly higher reaching 8 and 9 μg L-1 respectively in Keogh and Benson. These levels are above those estimated by Rescan (1991) which were determined only to be <5 μg L-1.

There is no indication in the present data that Benson Lake waters are enriched in dissolved metals compared to the control basin (Keogh), suggesting that the buried tailings on the lake floor may not be contributing a significant efflux of metals to the overlying water column. This observation is supported by the pore water profile data for Zn, Pb and Cd (Figures 3-15, 3-17 and 3-18), which show that in both basins the concentrations of these dissolved metals must decrease across the sediment-water interface. The high spatial resolution of the data near the core tops (5 mm sample interval) effectively rules out the possibility that the sampling missed a release of these

metals to bottom waters from the sediment surface. A variable and significant fraction of the metals occurs in the "colloidal" fraction (that portion of the <0.45 μm sample retained by a 0.1 μm filter), implying that our centrifugation technique was unable to separate particulate Zn, Pb and Cd completely from the aqueous phase. Similar observations were made (for Zn and Cu only) by Carignan et al. (1985) in a comparative methodological study of pore waters in Ontario lakes. Assuming steady-state (but note the "snapshot" caveat above) and that the metals measurements made in this study on the 0.1 μm-filter fraction more fairly represent the proportion of metals in true solution, it is concluded that dissolved Zn, Pb and Cd are diffusing into the sediments on the bottom of both Benson and Keogh lakes. This phenomenon has been observed previously in Canadian Shield lakes (Carignan and Nriagu 1985), in lacustrine sediments overlying buried tailings (Rescan 1990b), and in an actively-accumulating sulphide-rich tailings deposit (Rescan, 1990a)

A slightly different situation exists for copper. The near-surface maximum seen in the Keogh porewater data (Figure 3-16) indicates that copper is released to pore solution at a depth of about one centimetre. The shape of the profile implies that metal must be diffusing both upward and downward from this maximum. The flux of copper out of the sediments in this basin cannot be accurately estimated given the scatter in the data and the lack of measurement in the immediately overlying benthic boundary-layer. It is probably very low however, considering that the Cu concentration in the uppermost sample of the <0.1 μm filter-fraction is the same as that in the overlying supernatant; thus, no concentration gradient can be defined between about 2.5 mm depth and the bottom water. If this is a true feature, then upwardly-diffusing copper is being trapped in the top 5 mm of the deposits. Adsorption by Mn oxides is a likely candidate for such fixation. As noted earlier, about 1300 μg g^{-1} (0.13 wt. %) of "excess" (presumably oxide) Mn appears to be present in the top 5 mm of the Keogh core.

Copper concentrations measured in the <0.1 μm filter-fraction of pore waters from the top two centimetres of the Benson Lake deposits are the same as, or less than, that observed in the <0.1 μm fraction in the supernatant (Table D-1). The lack of a concentration gradient in the upward direction effectively rules out release of Cu to bottom water from the sediments.

The depletion of dissolved sulphate immediately below the sediment-water interface in both lakes suggests that precipitation of authigenic sulphide phases may be partly

responsible for limiting the dissolved metals levels in pore waters. However, the contribution from this quarter must be small and must be confined to the upper two centimetres, given the very low sulphate concentrations present in the lake waters and the invariant, barely detectable concentrations below ~2 cm depth. The solid-phase Mn/Al and Fe/Al ratio data suggest that iron and manganese oxides are accumulating in the top 5 mm in both lakes, via upward diffusion of Fe^{2+} and Mn^{2+} and oxidation and precipitation near the interface, as discussed in Section 4-1. Freshly-precipitated oxide phases have a high adsorptive capacity for dissolved metals (Balistrieri and Murray 1984; Kadko 1987); thus, oxide-scavenging of metals at the sediment-water interface can explain the depletion of Zn, Pb and Cd in the top pore water sample in both lakes relative to the already-low bottom water concentrations. As the oxides subsequently dissolve during shallow burial and release the adsorbed metals, the precipitation of trace quantities of sulphide minerals in the sulphate-reduction zone immediately below the zero-oxygen boundary may be responsible for limiting the dissolved Zn, Pb and Cd levels. Sequestration by sedimentary humic matter may also contribute to the removal of metals from pore solution.

The slightly different behaviour of copper may be related to a complexation effect. The "natural" sediments in both lakes are organic-rich, particularly in Keogh, and it would be expected that the associated pore waters contain abundant dissolved humic substances (humic and fulvic acids) which will tend to keep metals in solution as soluble complexes. At pH 7, Zn^{2+} and Cd^{2+} have significantly lower affinities for organic ligands in solution than Cu^{2+} or Pb^{2+} (Stumm and Morgan 1981), while Pb^{2+} has a much greater affinity for freshly-precipitated oxide surfaces than Cu^{2+} (as measured in seawater at pH 7.82; Balistrieri and Murray, 1984). Thus of these four metals, copper is more prone to remaining in solution as an organometallic complex; this may contribute to the contrast between the copper distribution in Keogh pore waters and those of Zn and Cd.

The origin of the subsurface Zn, Cu, Pb and Cd peaks in Benson Lake pore waters just above the tailings (Figures 3-15 to 3-18) is enigmatic. The maxima are defined by at least two adjacent samples in all cases, they are represented in both size fractions for each of the four elements, and a similar maximum appears to be present in the same depth interval in both the <0.45 and <0.1 μm iron profiles. Therefore, neither the presence of colloidal particles nor contamination can be reasonably invoked as explanations for the peaks. Similar maxima (in the <0.45 μm fraction only) were observed previously in cores collected from the submerged tailings in Buttle Lake, British Columbia (Rescan 1990c) and Mandy Lake, Manitoba (Rescan 1990b). At the time of reporting those data,

contamination by particulates was thought to be responsible, possibly resulting from ruptured filters. However, the samples in this study were double-filtered before acidification, the second time through the much more discriminating 0.1 µm pore size, and the peaks still persist. Further work, such as the insertion in the deposits of dialysis peepers with differing pore-size membranes, is required to determine the origin of these features.

5.0 CONCLUSIONS

Pyrite-rich mine tailings from the Coast Copper mine were discharged into Benson Lake from 1962 to 1973. The tailings in the central basin of the lake are now covered by about 30 cm of natural organic-rich sediments containing about 7 wt. % organic carbon. The relatively high C:N weight ratio (~22) indicates that the organic matter is largely of terrigenous origin. Nearby Keogh Lake is in a different watershed and never received input of any mining-related detritus. Sediments in the centre of this basin, which was sampled to provide a control site unimpacted by tailings, contain about 18 wt. % organic carbon. The organic fraction is partly terrigenous and partly planktonic, as indicated by a C:N weight ratio of ranging from 16-20.

A thin veneer of manganese and iron oxyhydroxide-rich material mantles the deposits in both basins. In Keogh, this layer appears to be at most 5 mm thick; in Benson, it may be slightly thicker.

High dissolved iron concentrations (relative to bottom water) at 1.5 cm depth in the Keogh deposits and below 1.5 cm in the Benson sediments indicate that the natural sediments are suboxic or anoxic at very shallow sub-bottom depths in both lakes.

Dissolved metal concentrations are low in the bottom waters of both lakes, being approximately equal to or less than B.C. MOE and/or CCREM guidelines. Sulphate levels are also very low, being <10 μmol L^{-1} in the bottom waters of both basins.

High-resolution profiles of dissolved Zn, Pb and Cd in the pore waters of both lakes show that concentrations of these metals decrease across the sediment-water interface, and are invariably lower than the levels measured in core-top (bottom) water. These data confirm that there is no efflux of these metals to the overlying water in either basin. Profiles of the dissolved copper concentration in pore waters suggest that some Cu may be diagenetically cycled just below the sediment-water interface in the Keogh deposits. Concentrations are low, however, and there is no indication of a benthic efflux of the metal. The Benson Lake profile yields a similar conclusion: there is no evidence of a benthic efflux of dissolved copper from the sediments to bottom waters in the lake despite the fact that the "natural" sediments accumulating at present, and progressively burying the tailings, still contain significantly higher concentrations of solid-phase copper than would be expected in a pristine basin.

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Appendix A: Detailed Core Descriptions

Rescan

APPENDIX A DETAILED CORE DESCRIPTIONS

BENSON LAKE CORE

The core was raised on August 7, 1991 from 46 m water depth at Station 1 toward the eastern end of the lake, sited by Rescan previously (Rescan, 1991). The total length of the core was 60 cm, and the interface was of good quality, being slightly domed. Shortly after collection, gas bubbles (probably methane) began to form in sediments from about 10 cm depth to the bottom of the core.

Log Description

0-0.2 cm: lightbrown organic fluff with worm tubes.

0.2-32 cm: homogeneous chocolate brown, with sporadic occurrences of fibrous twig-like material.

~32.5 - ~40 cm: grey tailings

40-41 cm: natural sediments

41-52 cm: grey tailings

52-54 cm: small amount of natural sediments (noticed during extrusion)

54-56 cm: grey tailings

56 cm - end: natural sediments

KEOGH LAKE CORE

The core was raised on November 30, 1991 from 43 m water depth in the approximate centre of the deep basin in the southwestern half of the lake, slightly west of Station 1 sited by Rescan previously (Rescan, 1991). The total length of the core was 57 cm, and the interface was of good quality, being slightly tilted. The supernatant water was clear upon core recovery, and freshwater shrimp were observed swimming just above the interface. Vertical organic fragments (possibly some form of worm tube?) were observed

in apparently true position protruding one or two mm from the interface Gas bubbles were not seen to form in the core after collection.

Log Description:

0-0.3 cm: burnt-sienna coloured fluffy surface veneer

0.3-4 cm: slightly olive-toned, pale-brown poorly-consolidated mud

4- 17 cm: uniform brown-olive mud

17-27 cm: dark chocolate-brown mud

27-33 cm: distinct gray layer, fine-grained? (During extrusion, this layer was observed between about 24 and 30 cm depth)

33 cm-end:dark chocolate-brown mud

Appendix B: Analytical Methods & Quality Control Data

APPENDIX B   ANALYTICAL METHODS AND 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 can be estimated by examining the results of repeat measurements, made on SLRS and on the same samples but on different days and with fresh calibration curves (Table B.1). Accuracy can be assessed by comparing the values measured in SLRS-2 (National Research Council of Canada Riverine Water Reference Material for Trace Metals) for this study with the recommended values 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 (1969), which eliminates the need to apply specific corrections for matrix absorption effects. The samples from the Keogh Lake core were extremely rich in organic matter which dilutes the silicate content to the point where an amorphous glass will not form. To obviate this problem, the

Table B-1
Quality Control Data for GFAAS Measurement of Dissolved Metal Concentrations in Benson and Keogh Lake Pore Waters

Sample	Mn	Fe	Cu	Zn	Pb	Cd
SLRS-2 (Meas.)	n.m.	n.m.	2.94	3.72	0.134	0.033
SLRS-2 (Meas.)			2.90			0.029
SLRS-2 (Rec.)	10.1 ± 0.3	129 ± 7	2.76 ± 0.17	3.33 ± 0.15	$0.129 + 0.011$	0.028 ± 0.004
Benson Super.				8.22, 7.90		0.56, 0.57
Benson 0.75 cm		9845, 10600		1.28, 1.33		0.10, 0.11
Benson 4.5 cm		41700, 42300		1.21, 1.53		0.12, 0.13
Benson 44 cm				1.90, 2.51		0.04, 0.02

Measurements are reported in mg L^{-1}. n.m. = not measured; Super - supernatant (core-top water). All values refer to the <0.45 µm filter fraction. Note that the SLRS standard was measured on different days using different calibration curves.

samples from this core only were precombusted at 800° C, the weight loss recorded and the residue used to make the glass discs. Corrections for the loss on ignition were subsequently applied to the raw XRF output.

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. 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). One gram samples were used for the top 4 samples in the Keogh Lake core as 4 grams were not available for these thin sampling intervals. Calibration was provided using 1 gram reference-standard discs. The top two samples (0 - 0.5 and 0.5-1 cm) in the Benson core were combined in equal proportions by weight to form a 4 g disc, as sample size for minor element analysis was also limiting here.

Analytical precision can be 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 runs for both cores. The results of these measurements are listed in Tables B.2a to B.2d.

Table B-2a

XRF Major Element Quality-Control Data, Benson Lake Samples

Standard		Fe	Ti	Ca	K	Si	Al	Mg	P	Na
AGV-1	(m)	4.84	0.65	3.50	1.93	28.26	9.13	0.89	0.21	1.64
	(r)	4.75	0.64	3.53	1.87	27.84	9.09	0.92	0.22	1.60
MRG	(m)	12.66	2.25	10.85	0.10	18.16	4.47	8.27	0.02	0.28
	(r)	12.47	2.21	10.56	0.12	18.36	4.50	8.13	0.03	0.26
DRN	(m)	6.64	0.64	4.93	1.12	24.50	9.10	2.54	0.09	1.14
	(r)	6.80	0.65	5.06	1.09	24.74	9.29	2.66	0.11	1.11
JB-2	(m)	10.05	0.70	7.00	0.26	23.77	7.28	2.56	0.05	0.65
	(r)	9.90	0.76	7.03	0.28	24.93	7.77	2.79	0.04	0.76
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 (1983).

Table B-2b

XRF Major Element Quality-Control Data, Keogh Lake Samples

Standard		Fe	Ti	Ca	K	Si	Al	Mg	P	Na
BE-N	(m)	8.81	1.54	9.87	0.86	17.37	4.81	6.70	0.44	0.60
	(r)	9.03	1.57	9.97	0.89	17.93	5.35	7.97	0.46	1.19
NIM-G	(m)	1.39	0.04	0.54	2.99	33.82	5.97	0.10	0.00	0.66
	(r)	1.41	0.05	0.56	3.19	35.35	6.39	0.04	0	1.25
W-2	(m)	7.41	0.61	7.59	0.40	22.88	7.24	3.23	0.05	0.45
	(r)	7.6	0.64	7.79	0.4	24.66	8.19	3.85	0.06	0.82

Concentrations determined for geochemical reference standards in this study (m) are compared with concentrations recommended (r) by Abbey (1983).

Table B-2c

XRF Minor Element Quality Control Data, Benson Lake Samples

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). Question marks indicate possibly unreliable values; n.a. = not available.

Table B-2c

XRF Minor Element Quality Control Data, Keogh Lake Samples

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). Question marks indicate possibly unreliable values; n.a. = not available.

CNS and CaCO3 Analysis

Total carbon, nitrogen and sulphur were determined using elemental analysis. Total C and N were measured using a Carlo-Erba 1106 Elemental Analyser which combusts the sample in a stream of O_2, separates the combustion gases (CO_2 and N_2 reduced from NO_x) chromatographically, and measures the gas concentrations (thus C and N contents) by thermal conductivity. Sulphur was determined using a Carlo-Erba NA-1500 CNS analyser, 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 analyser with SO_2. The analysers 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 (1s, 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 analyser, 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 (1 s, R.S.D.) was better than 3% for the higher carbonate carbon concentrations.

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

Appendix C: Sediment Chemistry Data

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APPENDIX C   SEDIMENT CHEMISTRY DATA

Table C-1

Major Element Composition in Sediments from Benson and Keogh Lake Cores

Interval cm	Depth cm	Fe Wt. %	Ti Wt. %	Ca Wt. %	K Wt. %	Si Wt. %	Al Wt. %	Mg Wt. %	P Wt. %	Na Wt. %
BENSON	**LAKE**	**CORE**								
0-0.5	0.25	9.02	0.70	3.12	0.91	21.49	7.71	1.66	0.13	1.32
0.5-1	0.75	8.25	0.68	3.17	0.75	21.44	7.61	1.64	0.12	1.28
1-1.5	1.25	8.14	0.68	3.02	0.79	21.38	7.60	1.66	0.11	1.21
1.5-2	1.75	8.06	0.68	3.00	0.75	21.43	7.70	1.67	0.12	1.13
3-4	3.5	8.13	0.67	3.35	0.76	20.85	7.55	1.53	0.12	0.97
5-6	5.5	7.65	0.64	3.27	0.72	20.12	7.22	1.47	0.13	0.90
8-10	9	7.87	0.68	3.07	0.59	20.65	7.36	1.90	0.12	1.04
12-14	13	7.92	0.71	3.00	0.61	22.05	7.68	1.97	0.12	1.09
16-18	17	8.14	0.71	2.94	0.56	21.04	7.54	2.01	0.12	1.02
20-22	21	8.87	0.67	4.13	0.52	20.22	7.15	2.09	0.11	1.03
22-26	24	8.48	0.65	3.49	0.51	19.29	6.93	1.93	0.11	0.96
26-30	28	10.25	0.62	5.47	0.51	18.89	6.77	2.08	0.11	0.88
30-34	32	13.38	0.46	7.35	0.37	19.74	5.42	2.50	0.08	0.69
34-38	36	16.56	0.31	10.17	0.22	20.76	3.70	2.95	0.05	0.37
42-46	44	17.23	0.30	11.88	0.20	20.37	3.56	2.68	0.04	0.30
50-54	52	14.76	0.34	11.83	0.22	20.63	3.98	3.23	0.06	0.32

Table C-1 (continued)

Major Element Composition in Sediments from Benson ad Keogh Lake Core

Interval cm	Depth cm	Fe Wt. %	Ti Wt. %	Ca Wt. %	K Wt.%	Si Wt.%	Al Wt.%	Mg Wt.%	P Wt.%	Na Wt.%
KEOGH	LAKE	CORE								
0-0.5	0.25	7.21	0.45	1.94	0.15	10.84	4.33	1.62	0.11	0.25
0.5-1	0.75	8.76	0.61	2.90	0.22	15.64	6.72	2.19	0.14	0.52
1-1.5	1.25	8.66	0.62	2.83	0.22	15.95	7.16	2.05	0.13	0.51
1.5-2	1.75	8.58	0.67	2.54	0.20	15.92	7.28	1.70	0.14	0.51
2-3	2.5	8.65	0.65	2.32	0.21	15.15	6.94	1.41	0.14	0.48
2-4	3.5	7.98	0.55	2.26	0.16	13.34	5.98	1.49	0.15	0.33
6-8	7	6.46	0.46	2.02	0.13	14.36	5.06	1.12	0.15	0.30
10-12	11	6.25	0.61	1.50	0.18	14.50	7.56	0.73	0.15	0.35
12-14	13	6.28	0.49	1.78	0.13	11.12	5.72	0.97	0.19	0.29
14-16	15	6.12	0.41	1.61	0.11	9.74	5.21	0.75	0.20	0.23
16-18	17	6.45	0.43	1.69	0.11	10.21	5.46	0.84	0.20	0.28
18-20	19	6.33	0.54	2.08	0.18	12.30	6.17	1.03	0.18	0.59
20-22	21	7.58	0.82	2.13	0.25	17.75	8.99	1.00	0.14	0.76
22-26	24	7.32	1.02	1.57	0.22	18.22	9.99	0.75	0.16	0.56
26-30	28	6.24	0.98	2.56	0.32	20.44	9.30	0.81	0.10	1.09
30-34	32	6.14	0.82	1.83	0.22	15.49	8.29	0.89	0.16	0.61
34-38	36	5.41	0.52	1.98	0.14	11.71	6.15	1.08	0.18	0.43
38-42	40	5.39	0.57	1.94	0.14	12.33	6.52	1.03	0.18	0.40
42-46	44	5.10	0.53	2.18	0.14	11.64	5.94	1.20	0.19	0.37
46-50	48	5.09	0.52	2.31	0.13	11.83	5.92	1.31	0.19	0.38
50-54	52	5.35	0.60	1.91	0.14	13.80	7.07	1.01	0.17	0.41

Table C-2

Major Element Weight Ratios in Sediments from Benson and Keogh 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
BENSON	**LAKE**	**CORE**						
0-0.5	0.25	1.17	0.091	0.405	0.118	2.79	0.215	0.172
0.5-1	0.75	1.08	0.089	0.417	0.098	2.82	0.215	0.168
1-1.5	1.25	1.07	0.089	0.398	0.104	2.81	0.219	0.159
1.5-2	1.75	1.05	0.088	0.389	0.098	2.78	0.217	0.147
3-4	3.5	1.08	0.088	0.444	0.101	2.76	0.203	0.128
5-6	5.5	1.06	0.089	0.454	0.100	2.79	0.203	0.124
8-10	9	1.07	0.092	0.417	0.080	2.80	0.258	0.141
12-14	13	1.03	0.093	0.390	0.080	2.87	0.256	0.142
16-18	17	1.08	0.095	0.390	0.075	2.79	0.267	0.135
20-22	21	1.24	0.094	0.578	0.073	2.83	0.292	0.144
22-26	24	1.22	0.094	0.503	0.074	2.78	0.278	0.139
26-30	28	1.51	0.092	0.808	0.076	2.79	0.307	0.130
30-34	32	2.47	0.085	1.357	0.068	3.64	0.462	0.127
34-38	36	4.48	0.084	2.752	0.059	5.62	0.797	0.099
42-46	44	4.84	0.084	3.338	0.057	5.72	0.752	0.085
50-54	52	3.71	0.086	2.975	0.055	5.19	0.812	0.081
KEOGH	**LAKE**	**CORE**						
0-0.5	0.25	1.665	0.100	0.448	0.034	2.500	0.374	0.058
0.5-1	0.75	1.305	0.090	0.432	0.033	2.329	0.326	0.077
1-1.5	1.25	1.210	0.086	0.395	0.030	2.229	0.287	0.071
1.5-2	1.75	1.178	0.093	0.349	0.027	2.187	0.234	0.070
2-3	2.5	1.247	0.093	0.334	0.030	2.184	0.204	0.069
2-4	3.5	1.334	0.092	0.377	0.027	2.232	0.249	0.055
6-8	7	1.276	0.092	0.400	0.025	2.838	0.222	0.058
10-12	11	0.826	0.080	0.198	0.024	1.917	0.096	0.046
12-14	13	1.099	0.086	0.311	0.023	1.943	0.170	0.050
14-16	15	1.176	0.080	0.309	0.021	1.871	0.145	0.044
16-18	17	1.183	0.080	0.309	0.020	1.871	0.155	0.051
18-20	19	1.026	0.088	0.337	0.030	1.993	0.167	0.095
20-22	21	0.843	0.092	0.237	0.027	1.974	0.112	0.085
22-26	24	0.732	0.102	0.158	0.022	1.824	0.075	0.056
26-30	28	0.672	0.105	0.275	0.034	2.199	0.087	0.117
30-34	32	0.741	0.099	0.221	0.027	1.869	0.107	0.074
34-38	36	0.879	0.084	0.321	0.023	1.903	0.175	0.069
38-42	40	0.826	0.088	0.298	0.021	1.892	0.159	0.062
42-46	44	0.858	0.089	0.367	0.024	1.960	0.202	0.062
46-50	48	0.861	0.088	0.390	0.022	1.999	0.222	0.065
50-54	52	0.757	0.084	0.270	0.020	1.953	0.144	0.058

Table C-3

Minor Element Composition of Sediments in Benson and Keogh Lake Cores

Interval cm	Depth cm	Zr ppm	Sr ppm	Rb ppm	Pb ppm	Zn ppm	Cu ppm	Ni ppm	Co ppm	Mn ppm	V ppm	Cr ppm	Ba ppm
BENSON LAKE													
0-1	0.50	125	323	27	14	154	164	36	49	2812	199	91	222
1-1.5	1.25	123	323	28	9	153	148	35	43	2837	199	89	215
1.5-2	1.75	124	325	28	15	163	159	36	45	2795	203	87	216
3-4	3.5	121	327	28	12	170	164	36	40	2908	204	87	208
5-6	5.5	122	321	28	19	181	170	33	40	2997	187	77	220
8-10	9	118	291	23	17	127	122	32	36	2436	210	93	218
12-14	13	123	305	22	10	133	134	36	35	1950	209	103	197
16-18	17	120	274	22	13	124	188	34	40	1985	212	101	209
20-22	21	113	259	19	10	111	262	34	43	2053	196	94	192
22-26	24	113	271	21	11	124	246	33	51	2078	203	98	216
26-30	28	103	258	17	5	111	330	31	44	2066	191	87	192
30-34	32	72	175	12	3	70	439	31	64	2034	134	69	120
34-38	36	51	121	6	n.d.	47	444	27	77	1966	89	50	52
42-46	44	51	115	5	n.d.	30	317	22	57	1867	75	35	57
50-54	52	56	133	6	n.d.	30	218	28	50	1985	79	41	41

Table C-3 (continued)
Minor Element Composition of Sediments in Benson and Keogh Lake
Cored

Interval cm	Depth cm	Zr ppm	Sr ppm	Rb ppm	Pb ppm	Zn ppm	Cu ppm	Ni ppm	Co ppm	Mn ppm	V ppm	Cr ppm	Ba ppm
KEOGH	**LAKE**												
0-0.5	0.25	68	113	7	11	86	135	98	71	3080	325	215	199
0.5-1	0.75	96	146	7	7	105	165	110	60	2580	320	218	235
1-1.5	1.25	92	117	7	7	80	143	80	55	2560	301	204	264
1.5-2	1.75	140	116	6	14	89	165	87	56	2450	289	168	296
2-3	2.5	112	117	9	10	84	164	62	61	2401	325	183	222
3-4	3.5	90	113	8	15	97	203	76	65	2481	317	186	172
4-5	4.5	78	105	9	10	81	139	71	59	2404	328	189	157
5-6	5.5	74	88	7	12	81	108	69	59	2574	296	178	158
6-8	7	64	96	6	10	70	83	61	45	2507	302	184	136
8-10	9	119	90	7	9	81	63	52	39	2632	286	168	199
10-12	11	212	106	10	8	95	57	44	35	2268	233	132	315
12-14	13	100	96	9	8	84	75	57	63	2827	353	180	204
14-16	15	80	88	6	6	80	65	55	84	3016	367	171	197
16-18	17	86	93	6	6	83	73	60	94	2956	365	176	195
18-20	19	115	122	7	8	85	68	62	65	2430	339	185	220
20-22	21	246	164	18	10	109	66	56	63	1570	229	133	322
22-26	24	336	140	16	13	112	63	46	33	1474	195	108	397
26-30	28	230	253	13	11	90	40	33	26	1258	165	105	327
30-34	32	203	142	13	6	91	53	46	37	1699	208	132	320
34-38	36	104	100	6	8	81	56	62	43	2224	322	207	206
38-42	40	118	101	6	7	80	52	57	41	2089	300	198	203
42-46	44	76	106	6	4	77	62	66	44	2220	352	243	156
46-50	48	72	106	6	6	74	55	67	42	2146	348	247	163
50-54	52	157	115	12	9	93	62	59	41	1875	279	182	231

n.d. = not detectable

Table C-4

Organic Carbon, Nitrogen, Sulphur and Calcium Carbonate Concentrations in Sediments from Benson and Keogh Lake Cores

Interval cm	Depth cm	CaCO3 Wt. %	N Wt. %	S Wt. %	Corg Wt. %	C/N Wt. Ratio
BENSON	LAKE	CORE				
0-0.5	0.25	0.24	0.30	0.21	6.74	22.7
0.5-1	0.75	0.26	0.29	0.20	6.57	22.9
1-1.5	1.25	0.23	0.28	0.18	6.50	23.3
1.5-2	1.75	0.21	0.27	0.17	6.54	23.9
3-4	3.5	0.58	0.30	0.21	7.10	23.5
5-6	5.5	0.65	0.35	0.20	8.93	25.7
8-10	9	0.24	0.37	0.20	8.32	22.3
12-14	13	0.33	0.30	0.20	6.44	21.5
16-18	17	0.38	0.35	0.21	7.50	21.6
20-22	21	0.13	0.34	0.27	7.65	22.6
22-26	24	0.07	0.31	0.26	7.04	22.5
26-30	28	0.26	0.29	0.28	6.82	23.5
30-34	32	0.17	0.20	1.04	4.62	23.0
34-38	36	0.57	0.06	1.69	0.70	12.7
42-46	44	0.53	0.03	1.77	0.35	10.8
50-54	52	0.52	0.04	1.14	0.56	14.1
KEOGH	LAKE	CORE				
0-0.5	0.25	0.32	0.79	0.27	12.29	15.56
0.5-1	0.75	0.17	0.66	0.19	10.35	15.80
1-1.5	1.25	0.42	0.62	0.27	10.51	16.94
1.5-2	1.75	0.50	0.60	0.21	10.05	16.74
2-3	2.5	0.33	0.65	0.23	11.16	17.29
3-4	3.5	0.17	0.85	0.33	15.35	18.16
4-5	4.5	0.25	0.87	0.58	16.13	18.53
5-6	5.5	0.25	0.97	0.69	17.76	18.30
6-8	7	0.17	0.93	0.63	17.69	19.12
8-10	9	0.17	1.04	0.34	19.81	19.05
10-12	11	0.17	0.74	0.25	14.40	19.45

Table C-4 (continued)

Organic Carbon, Nitrogen, Sulphur and Calcium Carbonate Concentrations in Sediments from Benson and Keogh Lake Cores

Imterval cm	Depth cm	$CaCO_3$ Wt. %	N Wt. %	S Wt. %	C_{org} Wt. %	C/N Wt. Ratio
KEOGH	LAKE	CORE	CONT'D			
12-14	13	0.25	1.08	0.34	20.86	19.31
14-16	15	0.17	1.27	0.42	22.91	18.11
16-18	17	0.25	1.15	0.37	22.54	19.60
18-20	19	0.33	1.00	0.34	18.20	18.20
20-22	21	0.17	0.47	0.18	8.02	17.06
22-26	24	0.17	0.29	0.09	5.59	19.28
26-30	28	0.08	0.27	0.01	6.07	22.48
30-34	32	0.17	0.63	0.18	12.21	19.38
34-38	36	0.25	1.02	0.29	19.53	19.15
38-42	40	0.17	0.92	0.26	18.90	20.54
42-46	44	0.25	1.02	0.30	20.63	20.23
46-50	48	0.50	1.02	0.29	20.36	19.96
50-54	52	0.25	n.m.	0.23	n.m.	n.m.

Appendix D: Metals Analyses in Interstitial Waters

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APPENDIX D   INTERSTITIAL WATER CHEMISTRY

Table D-1

Interstitial Water Chemistry Benson and Keogh Lake Cores

Depth cm	Fe <0.45μ μg L⁻¹	Fe <0.1 μ μg L⁻¹	Mn <0.45μ μg L⁻¹	Mn <0.1 μ μg L⁻¹	Cu <0.45μ μg L⁻¹	Cu <0.1 μ μg L⁻¹	Zn <0.45μ μg L⁻¹	Zn <0.1 μ μg L⁻¹	Pb <0.45μ μg L⁻¹	Pb <0.1 μ μg L⁻¹	Cd <0.45μ μg L⁻¹	Cd <0.1μ μg L⁻¹
BENSON	**LAKE**	**CORE**										
Super	1177	1157	1900	1712	1.34	1.21	8.22	7.90	1.18	0.97	0.557	0.431
0.25	10500	n.m.	4235	n.m.	2.47	n.m.	1.71	n.m.	0.43	n.m.	0.103	n.m.
0.75	10600	n.m.	6610	n.m.	1.56	n.m.	1.28	n.m.	0.39	n.m.	0.101	n.m.
1.25	17200	16700	9315	7856	3.40	1.36	1.83	1.10	0.39	0.15	0.155	0.062
1.75	19600	n.m.	10645	n.m.	1.06	n.m.	0.93	n.m.	0.26	n.m.	0.095	n.m.
2.5	27100	26600	11130	11944	1.70	1.00	1.19	n.m.	0.32	0.11	0.152	n.m.
3.5	35400	34200	14470	15444	1.77	0.50	1.08	n.m.	0.20	0.04	0.113	n.m.
4.5	42300	41000	16225	17844	1.79	0.72	1.21	n.m.	0.21	0.09	0.122	n.m.
5.5	50100	46100	17650	18156	5.43	0.71	2.92	1.86	0.42	0.05	0.175	0.046
7	71700	68900	18250	19596	5.36	0.99	2.80	3.31*	0.42	0.15	0.406	0.100
9	77700	75800	14700	16320	1.73	0.57	1.85	n.m.	0.28	0.12	0.169	0.042
11	66800	67000	10395	10432	0.92	0.20	0.87	n.m.	0.20	0.12	0.047	0.021
13	57900	56700	7505	7108	1.00	0.67	1.36	1.68*	0.22	0.04	0.088	0.028
15	48500	45500	5755	5540	6.35	0.53	3.26	1.20	0.57	0.07	0.153	0.017
17	48200	46400	5900	5684	5.15	1.30	1.86	1.04	0.34	0.14	0.103	0.027
19	43300	41700	5575	5372	3.62	1.42	1.44	1.25	0.23	0.15	0.062	0.042
21	44800	45000	5365	5236	6.97	3.46	1.19	2.04*	0.35	0.22	0.114	0.079
24	67700	57400	5920	5720	7.20	3.85	1.46	2.13*	0.39	0.19	0.135	0.076
28	59700	55200	5665	5588	25.87	6.15	3.16	2.53	0.99	0.24	0.386	0.132
32	61800	51300	5130	5376	23.96	12.33	2.06	1.97	0.67	0.31	0.230	0.132
36	52000	49600	4365	4252	6.39	3.07	0.72	1.63*	0.21	0.11	0.037	0.035
40	48200	47300	3570	3508	6.14	3.83	2.03	1.20	0.19	0.20	0.043	0.030
44	41100	40600	2680	2612	19.99	0.12	1.90	1.07	0.30	0.11	0.019	0.008
48	36600	35200	2060	2016	n.m.	0.11	0.32	0.79*	0.19	0.13	0.003	0.007
52	35450	35350	2350	2296	6.44	4.26	0.43	1.17*	0.21	0.06	0.061	0.023

Table D-1 (continued)

Interstitial Water Chemistry Benson and Keogh Lake Cores

Depth cm	Fe <0.45μ μg L⁻¹	Fe <0.1 μ μg L⁻¹	Mn <0.45μ μg L⁻¹	Mn <0.1 μ μg L⁻¹	Cu <0.45μ μg L⁻¹	Cu <0.1 μ μg L⁻¹	Zn <0.45μ μg L⁻¹	Zn <0.1 μ μg L⁻¹	Pb <0.45μ μg L⁻¹	Pb <0.1μ μg L⁻¹	Cd <0.45μ μg L⁻¹	Cd <0.1μ μg L⁻¹
KEOGH	LAKE	CORE										
Super	1160	639	435	407	1.52	1.56	9.28	21.02*	0.52	0.39	0.072	0.055*
0.25	5820	579	1025	1067	2.46	1.61	1.69	2.33*	0.21	0.14		0.013*
0.75	7255	6280	1345	1451	4.18	2.98	1.44	1.65*	0.20	0.19	0.007	0.008*
1.25	62000	8800	14900	8900	3.66	3.62	1.34	16.51*	0.28	0.28	0.009	0.056*
1.75	16200	5030	17600	12500	1.80	1.89	0.49	10.50*	0.17	0.18	0.003	0.027*
2.5	18800	5870	4200	9700	1.98	1.69	0.35	1.01*	0.11	0.17	0.004	0.005
3.5	7185	6150	1245	1188	2.40	1.73	0.44	1.66*	0.21	0.12	0.000	0.008*
4.5	9170	8880	765	1211	2.88	2.19	0.95	13.47*	0.14	0.22	0.005	0.028*
5.5	4950	6130	425	806	1.59	1.37	1.73	5.66*	0.27	0.12	0.008	0.014*
7	7590	7650	795	1751	1.27	2.11	0.56	1.33*	0.12	0.07	0.002	0.005*
11	7310	5940	805	462	1.25	1.13	0.74	0.99*	0.17	0.05	0.004	0.004
15	5480	4580	615	275	2.41	2.12	0.74	1.42*	0.15	0.06	0.006	0.004
19	8590	7610	720	411	0.72	0.66	0.23	2.33*	0.12	0.04	0.003	0.004
24	12040	n.m.	890	n.m.	1.60	n.m.	1.45	n.m.	0.21	0.05	0.009	n.m.
32	24520	n.m.	1285	n.m.	0.91	n.m.	0.23	n.m.	0.12	n.m.	0.004	n.m.
40	21010	n.m.	1495	n.m.	1.57	n.m.	0.77	n.m.	0.08	n.m.	0.005	n.m.
48	21050	n.m.	1405	n.m.	2.44	n.m.	0.56	n.m.	0.14	n.m.	0.003	n.m.

*Measurements marked with an asterisk are thought to reflect contamination, based on criteria defined in the text. n.m. = not measured.