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Response of Lake Sediments to Changes in Trace Metal Emissions from the Smelters at Sudbury, Ontario

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by

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EXECUTIVE SUMMARY

One of the associated effects of acid precipitation in aquatic ecosystems is the increased loading of metals reflected by increased rate of accumulation in the most recent (0-14 cm) layers of sediments. Lake sediment ecosystems which are major sinks for these pollutants have therefore become prime focus of studies to understand and ascertain historical changes in lake biogeochemistry and ecology associated with acid precipitation.

Changes in rates of toxic metal inputs may lead to a long-term recovery of the lakes in the Sudbury basin. Lake acidification affects certain microbial populations resulting in reduced microbial respiration and organic matter biodegradation in lake sediments (Rao et al., 1984-A). Another objective of the study was to document any changes in microbial processes which can be attributed to the recent reduction in the flux of metals into the lake sediments.

Historical records preserved in sediments show that the lakes are extremely sensitive to metal emissions from the smelters in the Sudbury basin. From the observed quick response, a strong capacity for rapid recovery (de-acidification) of acid-stressed lakes in the area is deduced. The study thus emphasizes the need for curtailing the emissions of acidic and acidifying substances as a critical step in reducing lake acidification as well as in rehabilitating many of the afflicted lakes.

RÉSUMÉ EXÉCUTIF

Un des effets des pluies acides sur les écosystèmes aquatiques est l'augmentation des charges de métaux, qui se manifeste par un accroissement de la vitesse d'accumulation des métaux dans les couches les plus récentes (0 à 14 cm) de sédiments. L'étude des sédiments lacustres, sur lesquels se fixent la plus grande partie de ces métaux polluants, est donc devenue un élément essentiel pour comprendre et vérifier les changements biochimiques et écologiques imputables aux pluies acides qui surviennent dans les lacs au fil des années.

Une modification de la vitesse de déversement des métaux toxiques pourrait, à la longue, conduire à une restauration des lacs du bassin de Sudbury. L'acidification des lacs nuit à certaines populations de micro-organismes en réduisant leur capacité respiratoire et en provoquant une biodégradation de la matière organique dans les sédiments lacustres (Rao et coll., 1983). L'étude a également pour objectif de recueillir des données sur toutes les modifications dans le métabolisme des micro-organismes pouvant être attribuées à une récente diminution du déversement des métaux sur les sédiments lacustres.

Les données historiques recueillies lors de l'étude des sédiments démontrent que les lacs sont extrêmement sensibles aux émissions de métaux des hauts fourneaux du bassin de Sudbury. En se basant sur la rapidité des réactions observées, on peut en déduire que les lacs acides de la région possèdent une grande capacité de restauration (désacidification). L'étude permet donc de conclure que la réduction des émissions de substances acides et acidifiantes est une étape importante du programme de réduction de l'acidification des lacs et de restauration d'un grand nombre de lacs déjà pollués.

ABSTRACT

Historical records preserved in sediments show that the lakes are extremely sensitive to metal emissions from the smelters in the Sudbury basin. From the observed quick response, a strong capacity for rapid recovery (de-acidification) of acid-stressed lakes in the area is deduced. The study thus emphasizes the need for curtailing the emissions of acidic and acidifying substances as a critical step in reducing lake acidification as well as in rehabilitating many of the afflicted lakes.

RÉSUMÉ

Les données historiques recueillies lors de l'étude des sédiments démontrent que les lacs sont extrêmement sensibles aux émissions de métaux des hauts fourneaux du bassin de Sudbury. En se basant sur la rapidité des réactions observées, on peut en déduire que les lacs acides de la région possède une grande capacité de restauration (désacidification). L'étude permet donc de conclure que la réduction des émissions des substances acides et acidifiantes est une étape importante du programme de réduction de l'acidification des lacs et de restauration d'un grand nombre de lacs déjà pollués.

Titre : Réactions des sédiments lacustres aux modifications des émissions de métaux à l'état de trace des hauts fourneaux à Sudbury (Ontario).

INTRODUCTION

The concern for the impacts of smelting activities on aquatic ecosystems near Sudbury, Ontario has led to many biogeochemical studies in the surrounding lakes (see Nriagu, 1984). The lakes in the area exhibit wide diversity in geochemical and biochemical characteristics and show varying degrees of stress from acid precipitation (Gorham and Gordon, 1960; Beamish and Harvey, 1972; Conroy et al. 1978).

One of the associated effects of acid precipitation in aquatic ecosystems is the increased loading of metals reflected by increased rate of accumulation in the most recent (0-14 cm) layers of sediments. Lake sediment ecosystems which are major sinks for these pollutants have therefore become prime focus of studies to understand and ascertain historical changes in lake chemistry and ecology associated with acid precipitation. It should be noted in this connection that lake sediments generally preserve a good historical record of changes in the fluxes of heavy metals in lake basin (MARC, 1985).

Historically, many lakes near Sudbury, Ontario have been adversely affected by mining and smelting activities. Mining and smelting of the Ni/Cu ores at Sudbury began to release trace metals into the surrounding environments around 1883 (Semkin and Kramer, 1976; Nriagu et al., 1982). By the late 1960s, the impacts of the emissions on the surrounding ecosystems had become alarming, and a

381 m superstack was built in 1972 as some sort of corrective measure. Today, the broadcasting of emissions to a much wider area by the superstack and the reduction in particulate emissions have greatly reduced the fallout of pollutant metals in the Sudbury basin (Chan and Lusis, 1985). The reduced metal deposition rate should be recorded in the lake sediments, and this study is aimed at documenting such a phenomenon. How fast the sediments respond to reduced metal emission should serve as a pointer to the ease of recovery of many of the acid-stressed lakes.

Changes in the deposition rates of toxic metal inputs may lead to a long-term recovery of the lakes in the Sudbury basin. Lake acidification affects certain microbial populations resulting in reduced microbial respiration and organic matter biodegradation in lake sediments (Rao et al., 1984-B). Another objective of the study was to document any changes in microbial processes which can be attributed to the recent reduction in the flux of metals into the lake sediments.

MATERIALS AND METHODS

Sediment cores were collected during the summer of 1985 from acid stressed Silver Lake and non-acid stressed Mcfarlane Lake using lightweight coring device (Williams and Pashley, 1979). Only cores that came up with their sediment-water interfaces intact and undeformed were processed. Each intact core was subsectioned and transported under ice and subsequently analyzed.

The digestion of the sediment samples was performed in teflon lined Parr Digestion Bombs (Agemian and Chau, 1976) and the metal concentrations in the leachates were determined by atomic absorption spectrometry (Nriagu et al., 1982). Oxygen consumption by the various sediment fractions was measured at 20°, using Gilson Differential Respirometer. Sediment microbial populations were determined using the plate count procedure (Dutka, 1978). The pH measurements were made using a portable pH meter with the electrode immersed directly into the mud during the extrusion. Organic carbon content of the sediment was measured by dry combustion following the standard procedure (APHA, 1980).

RESULTS AND DISCUSSION

The profiles of Ni, Pb, Co and Zn in sediments show that the sharp increase in the deposition rates started at a depth of 13-14 cm in the two lakes (Figure 1). This implies that the rates of sediment accumulation in the two lakes are very similar. The accelerated flux of metals into lake sediments in the Sudbury basin has been linked to the local smelting of the Ni/Cu ores which commenced in 1890 or so (Nriagu et al., 1982; Dillon and Smith, 1984). If the 13-14 cm horizon corresponds to the 1890, the sedimentation rate is estimated to be 1.4 mm/yr. This value is in reasonable agreement with the rate of 1.00 mm/yr (uncompacted) obtained by lead-210 geochronology for McFarlane Lake sediments (Nriagu _et al_., 1982).

Previous authors have already noted that the Ni contents of recent lake sediments in the Sudbury basin (see Figure 1) are among the highest in North America. The slopes of the Ni profiles during the period of rapid increase are remarkably similar in the two lakes. The actual amount of Ni stored, however, is always greater in McFarlane Lake compared to Silver Lake sediments. From the sedimentation rate of 157 $gm^{-2}yr^{-1}$ (Nriagu _et al_., 1982) and the concentrations given in Figure 1, it can be shown that until very recent years, the flux of Ni into McFarlane Lake sediments increased at the rate of about 1.3 mg $m^{-2}yr^{-1}$. The increased loading of Ni into the sediments thus seems to reflect the expanding production of Ni and Cu from Sudbury.

From 1890 until very recently, the accumulation of Co in McFarlane Lake sediments increased at the rate of about 0.6 $mg^{-2}yr^{-1}$. This heavy influx is rather unexpected since the mining and smelting operations in Sudbury have yet to be widely recognized as a major source of pollutant Co in the Canadian environment. These operations do not emit large quantities of Zn and the gradual increase in the Zn content of the sediments can be attributed to general environmental pollution in the neighbourhood of an urban centre (Sudbury). At present, emissions from the smelters in the Sudbury basin include Cu=670, Ni=500, Pb=204, Zn=66 and Cd=32 tonnes/yr (Chan and Lusis, 1985). These emission rates match the observed relative flux of metals into the sediments.

The most interesting feature of the profiles is the sharp decline in the metal content of the most recent (surficial) sediments. The decline in relation to the observed maximal concentrations vary from over 40% (Ni in Silver Lake and Co in McFarlane Lake) to about 15% (Zn in McFarlane Lake). The erection of the 381 m "superstack" in 1972 has been shown to significantly reduce the local deposition of metals and other pollutants released from the smelters in the Sudbury basin (Kramer, 1976; Semkin and Kramer, 1976; Nriagu et al., 1982). The observed decrease in metal flux to the sediments obviously must be related to improvements in local air quality brought about by the superstack. This means that these sediments are extremely sensitive to short-term changes in rates of metal deposition into the lakes' basins. In fact, the 15-40% decrease derived from the sedimentary record is in reasonable agreement with estimates based on changes in local atmospheric fallout measurements (cf. Kramer, 1976 and Chan and Lusis, 1985).

There are, however, problems in the actual interpretation of the historical record depicted by the sedimentary profiles. For example, the decline in both the Ni and Co accumulation in Silver Lake sediments began at about 4.0 cm below the sediment-water interface; this corresponds to about 27 years ago considering the sedimentation rate of 0.15 cm/yr. According to the sediment record also, the onset of reduced metal inputs into McFarlane Lake dates from 10 (Zn and Ni) to 27 (Co) years ago. It should further be noted that the decline in Ni accumulation seems to have started much earlier in Silver Lake compared to McFarlane Lake (Figure 1).

These inter-element and inter-lake differences suggest that (a) once deposited, the rate of which metals are redistributed depends on their biogeochemical properties, or (b) the profiles are primarly an expression of the mechanisms of diffusion into and precipitation of each metal in the sediments (Carigan and Nriagu, 1985). The dissolution and removal of metals from the surficial sediments in response to increased lake acidification cannot be a valid explanation for the profiles since McFarlane Lake has remained basically unaffected by the acid rain deposition. The point that needs to be emphasized, however, is that while the sediments are highly sensitive to changes in smelter emissions of metals, the relationship between the intensity of metal input and the records in sediments is quite complex and strongly influenced by the physico-chemical properties of both the sediments and the overlying lake water (see also, Nriagu and Wong, 1986).

The pH of McFarlane Lake sediments decreases from about 7.6 at the sediment-water interface to slightly under 7.0 below the 6-7 cm horizon (Figure 2). By contrast, the pH of Silver Lake increases from about 4.0 at the interface to a little over 5.0 below 5-6 cm. The differences in pH values and profiles may explain the observed higher rates of metal accumulation (or retention) in McFarlane compared to Silver Lake sediments (see Figure 1). It has been shown that pH values lower than 4.5 (typical of surficial sediments of Silver Lake) greatly reduce the retention of metals by sediment particles (Nriagu and Gaillard, 1984), and destabilize any metal compounds precipitated in such lake sediments (Arafat and Nriagu, 1986).

The effect of the reduced metal burden on microbial populations and microbial respiration in the surficial sediments is difficult to resolve. There is a marked increase in biomass of aerobic heterotrophs and sediment oxygen demand (McFarlane only) in the most recent sediments (Figure 1). This increase apparently is not supported by a corresponding enrichment in the organic matter content of the sediments. If anything, the observed decline in the organic matter content of the surficial sediments of Silver Lake may be attributed to enhanced biodegradation stemming from the recent increase in microbial populations. It should nevertheless be noted that the population of aerobic heterotrophs is about two orders of magnitude lower in the acid-stressed Silver Lake compared to the sub-alkaline McFarlane Lake and that the change in bacterial activity with depth does not exactly parallel the metal profiles in the Silver Lake sediments (Figure 2).

METAL PROFILES AND REVERSIBILITY OF LAKE ACIDIFICATION

This study clearly demonstrates that the lake sediments are extremely sensitive to changes in the emissions of metals from the smelters in the Sudbury basin. Since the accumulation of the pollutant metals is also determined by the physical-chemical properties of the sediments and the overlying water, one can surmise that the entire lake ecosystem responds quite quickly to changes in intensity of metal emission or input. The observed historical records in sediments therefore provide *de facto* evidence that much of the damage suffered by aquatic ecosystems in the area are quickly reversible. Other studies have also noted an increase in pH and a decrease in sulfate levels in lakes of the Sudbury basin which can be attributed to reduced SO_2 emissions from the smelters (LaZerta and Dillon, 1984; Yan and Miller, 1984).

The reversibility of lake acidification depends on the rapid response of the lake to reductions in acidic or acidifying emissions to the atmosphere. The trace metal data from the present study suggest that the impacted lakes are likely to recover quickly when emissions of polluting substances are reduced. This study is consistent with a recent study which has found rapid recovery (deacidification) of many acid-stressed lakes in western Sweden (Forsberg *et al*., 1985). These studies underscore the need for source control of SO_x and NO_x emissions as a critical step in reducing lake acidification.

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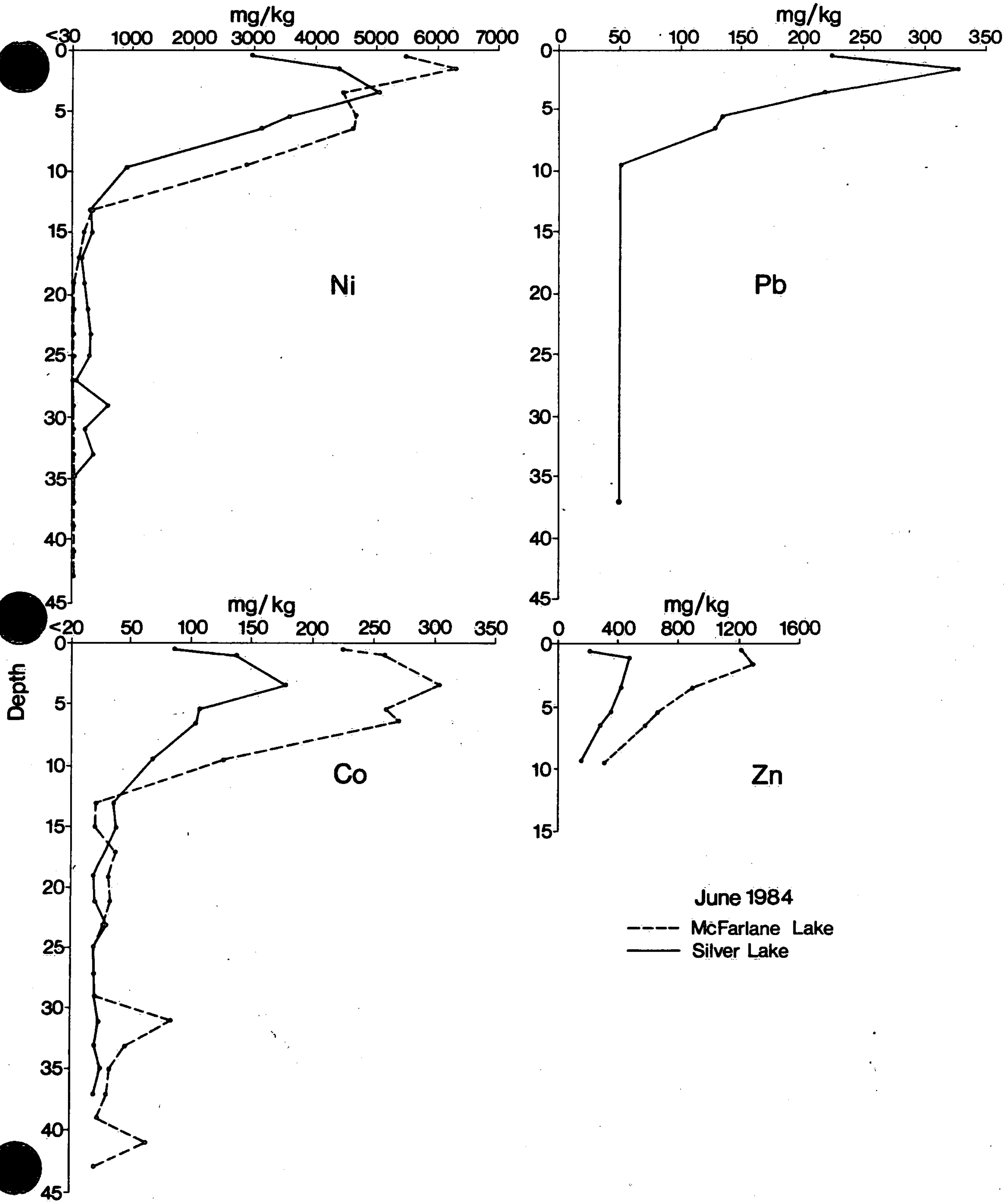

Figure 1

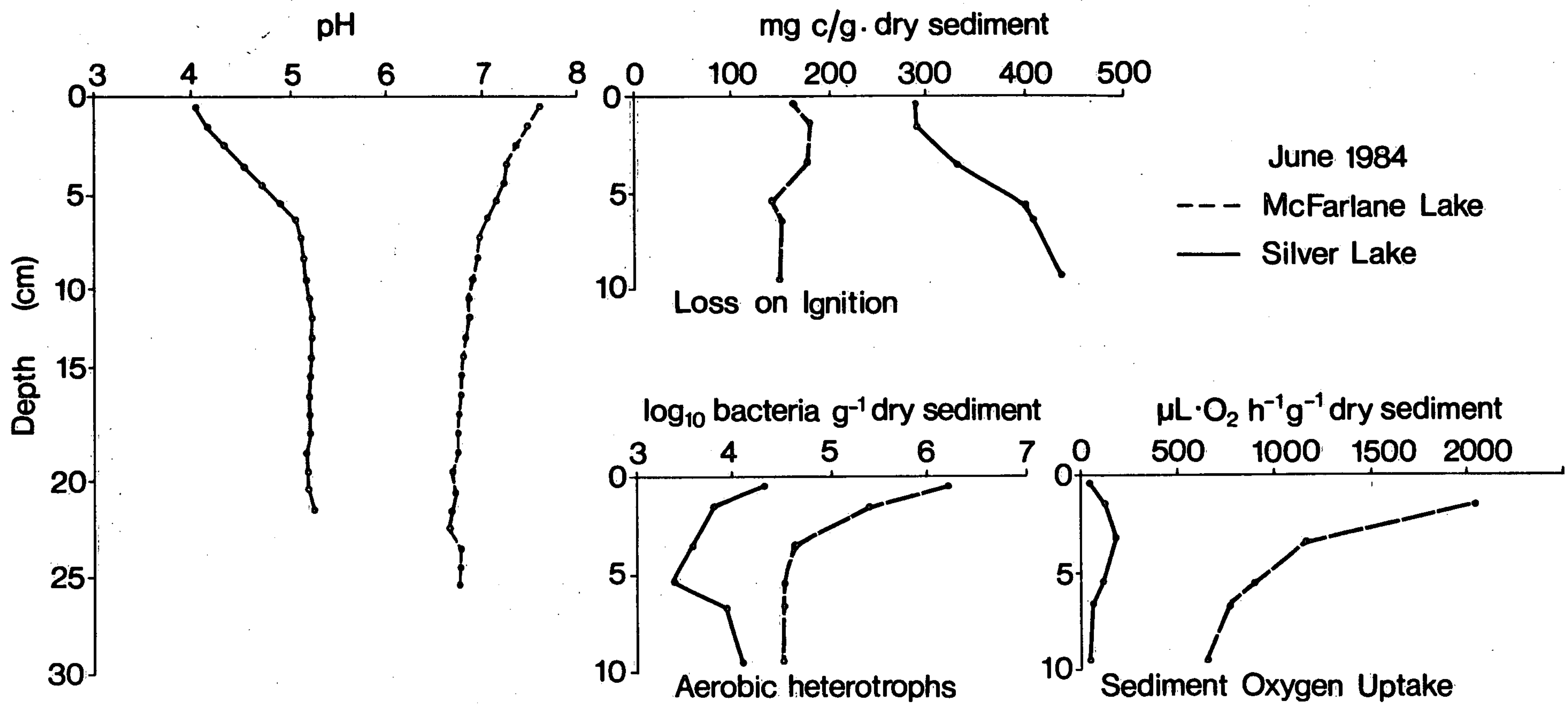
pH
3 4 5 6 7 8
0 5 10 15 20 25 30
Depth (cm)
mg c/g · dry sediment
0 100 200 300 400 500
0 5 10
Loss on Ignition
June 1984
McFarlane Lake
Silver Lake
log10 bacteria g-1 dry sediment
3 4 5 6 7
Aerobic heterotrophs
μL·O2 h-1g-1 dry sediment
0 500 1000 1500 2000
Sediment Oxygen Uptake

Figure 2