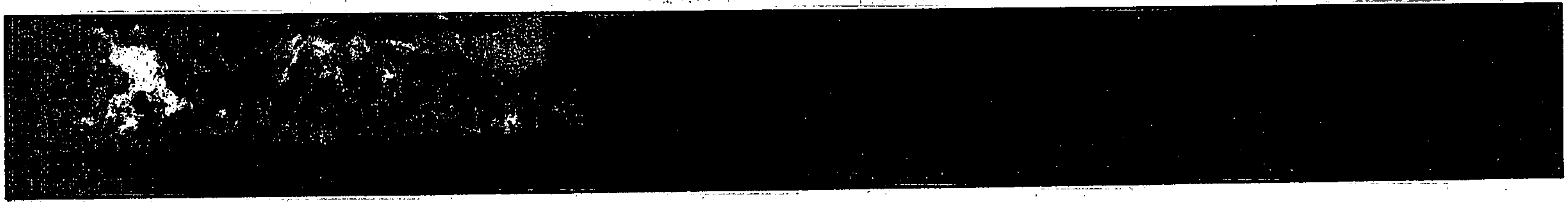

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ASSESSMENT OF HEAVY METAL INPUTS INTO LAKE SEDIMENTS IN NORTH-WEST QUEBEC FROM THE NORANDA MINING AND SMELTING OPERATIONS

Inland Waters Directorate **Direction Générale des Eaux Intérieures**

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by

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ABSTRACT

The Noranda copper smelter in Rouyn-Noranda, Quebec, is a major source of SO_2, emitting nearly 600,000 tonnes annually. This amount is equivalent to 70% of Quebec's SO_2 production, making this smelter the second largest point source of SO_2 in Canada. Heavy metals and other elements occur in sulfide ores. When these ores are smelted for their copper content, large amounts of heavy metals associated with the minerals are emitted into the atmosphere.

Results of sediment cores analysed from seven area lakes indicate high loading in the top 7 cm of sediment with Cu, Zn, Fe, Pb, and Mn in lakes near the smelter, and lower levels in lakes located further away within our 70 km radius study zone. Metal loadings were attributed to a variety of sources including mine tailings, land runoff, and aerial deposition.

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INTRODUCTION

The Rouyn-Noranda, Quebec, project was carried out to assess the general environmental impact of pollution from Noranda's smelter on the surrounding lakes. Noranda's two stacks spew out nearly 600,000 tonnes of sulfur dioxide (SO_2) annually, an amount equivalent to 70% of the province's total SO_2 production. It is second only to Inco in Sudbury, Ontario, for SO_2 emissions in Canada[1]. Heavy metals, as well as arsenic and selenium, are present in sulfide ores; upon smelting the ores for their copper content, large amounts of these ore-associated metals and non-metals are released into the atmosphere along with the SO_2.

A study of the pollution affects on the surrounding bog vegetation was carried out in 1981[2]. Our study concentrates on lake sediments and surface waters in the same area as that studied in 1981, in order to obtain an overall assessment of the smelter's environmental impact.

Both water samples and sediment cores were taken from lakes Preissac, Dufault, Osisko, Opasatica, Macamic, Chassignolle, and Duparquet, all of which are located within a 70 km radius of Rouyn-Noranda (Figure 1). Surface water was analysed for trace levels of Cu, Ni, Mn, Al, and Fe, and in selected cases As and Se. Major ions including Ca^{++}, Mg^{++}, Na^{+}, K^{+}, $SO_4^{=}$, Cl^{-}, and Alkalinity were

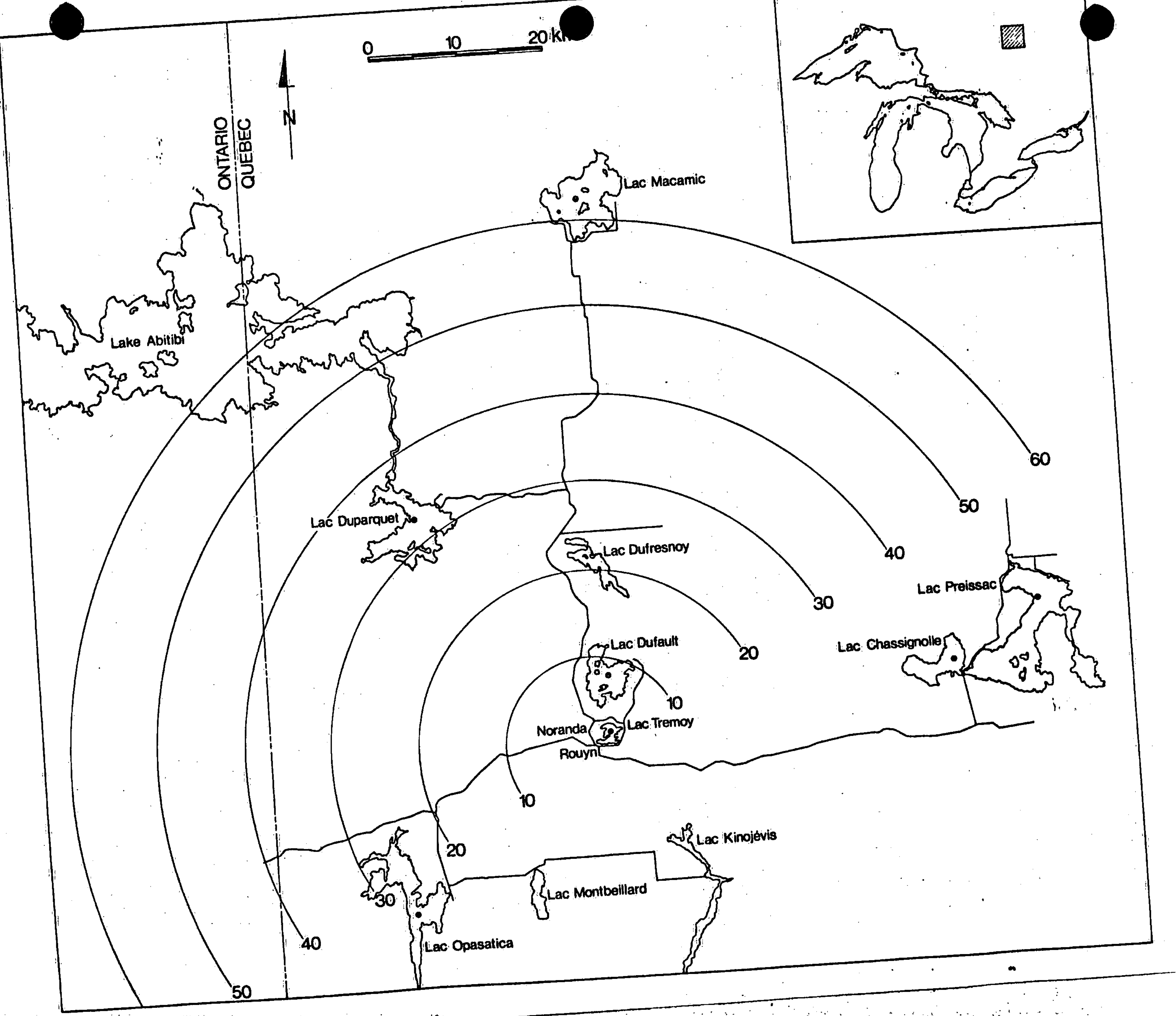

Figure 1. Rouyn-Noranda Study Area

also detected. In lake sediments, levels of Cu, Ni, Zn, Fe, Al, Cr, Cd, Pb, Mn, and Mo were determined. Eh and pH readings were taken, and X-ray diffraction analysis performed on samples from predetermined depths to obtain information on the mineralogical composition of the sediment. Levels of total organic and total inorganic carbon were also determined. On selected lakes, sediment particle size analysis and pollen counts were performed.

The study of the environmental impact of the mining/smelting industry in this region is not new. Environment Quebec has issued a series of reports dealing with this problem. Their E series report on Rouyn-Noranda[3] dealt with various aspects of the environmental problem, including metal deposition, precipitation chemistry and ecological and social aftereffects. Our report, while a general overview, contains complete metal deposition profiles for the sediment cores taken from seven lakes scattered in our 70 km radius study area. It includes some lakes previously studied by Environment Quebec. The lakes were chosen to determine if any pollution trends in the region predominate, and to evaluate if interprovincial transport of pollution can occur.

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METHODOLOGY

The sampling for this study was carried out in June of 1982. On lakes where no bathymetric maps were available, an echo-sounder was used to locate the maximum depth. Electronic Bathythermograph (EBT) profiles were obtained at each sampling station. Water and sediment temperatures were also recorded.

Surface water samples for trace element analysis (Cu, Ni, Mn, Al, Fe, As, and Se) were collected in 1 L polyethylene bottles prewashed with dilute HNO_3, distilled water and acidified with 2 mL of conc. HNO_3. For major ion analysis (Ca^{++}, Mg^{++}, Na^{+}, K^{+}, $SO_4^{=}$, Cl^{-}, SiO_2 and Alkalinity), water samples were collected in 100 mL polyethylene bottles, prewashed with dilute HNO_3 and distilled water. Surface water pH readings were taken at each sampling station. The water analysis was carried by the Water Quality Branch, Environment Canada (Ontario region) in Burlington, Ontario.

Sediment cores were obtained using a Benthos gravity corer equipped with a 5 cm diameter plastic liner. Each core was subsectioned on site into approximately 1 cm layers to a depth of 25 cm. Eh and pH readings were taken on the 0-1 cm and 6-7 cm sections (spot checks at lower depths indicated nearly constant Eh and pH and therefore only the two readings were recorded). Each 1 cm section was placed in a self-sealing plastic bag and put on ice until returned to the laboratory. Prior to processing, the samples were kept frozen. Samples were initially freeze-dried and then subjected to appropriate analyses. To determine sediment mineral composition, x-ray diffraction analysis was carried out. Levels of total organic and total inorganic carbon were determined using a Leco Carbon Analyser. On both the Lac Dufault and Lac Chassignolle cores, particle size analysis using the sieve and sedigraph method[4] and pollen counts[5] were performed.

The concentrations of the following heavy metals in the sediments were determined: Fe, Cu, Mn, Zn, Al, Cr, Ni, Mo, Pb and Cd. To extract the metals from the sediment, the freeze-dried samples were initially ground to 200 mesh size. Then, 0.8 g of the sample was placed into a clean 125 mL Erlenmeyer flask containing anti-bumping glass beads. To the flask, 25 mL of 3:1 $HCl:HNO_3$ (aqua regia) was added. Heating was done initially at 50°C on a hotplate/shaker until the orange foaming ceased; the temperature was then raised over a 20 minute period to 150°C where it was maintained until 3-5 mL of solution remained. The flask was then cooled to room temperature and the extraction procedure repeated, i.e. the acid mixture was added and the solution boiled down to the required volume. The digested sample, together with the residue, was rinsed into a 100 mL plastic centrifuge tube with double-distilled water. The tube was centrifuged at 12000 rpm for 15 minutes after which the supernatent was decanted into a

100 mL volumetric flask. The residue was washed with double-distilled water, centrifuged again at 12000 rpm for 15 minutes, and the washing added to the volumetric flask containing the initial extract. Double-distilled water was used to dilute to volume. The samples were analysed using a Varian AA-775 Series Flame Atomic Absorption Spectrophotometer using the parameters quoted in the company's analytical methods book. The samples from lakes Osisko and Macamic were analysed in triplicate; when good reproducibility was found (see Table 1) the remaining core samples were analysed in duplicate.

RESULTS AND DISCUSSION

Lac Osisko (also known as Lac Tremoy)

Located 1.5 km south of the smelter at 48°19'N, 70°00'E, Lac Osisko is subjected not only to industrial pollution through aerial deposition and seepage from mine-tailing ponds, but also to municipal waste discharges. The Benthos core was obtained from a depth of 8 m with the EBT profile indicating isothermal conditions in the water column. The 0-1 cm sediment layer was found to have reducing conditions (Eh-110 mV) and pH 6.6 while at 6-7 cm oxidizing conditions (Eh + 160 mV) were exhibited with a pH of 6.5.

Significant enrichment in the metals Cu, Zn and Fe (Figures 2(a), (b)) was observed over the 0-6 cm depth range (see Table 4). Transition to background levels was found to occur in the 6-7 cm section. Maximum levels of 7297 μg/g, 14469 μg/g and 246750 μg/g were observed for Cu, Zn and Fe respectively. Cd and Pb (Figures 2(c), (d)) were detectable only to the 5 cm depth. Maximum levels of 132 μg/g and 1609 μg/g for Cd and Pb respectively were found in the top layers.

The Mn (Figure 2(d)) profile shows the metal concentration over the 0-6 cm depth range to be lower than the background level. This behaviour can be better understood by considering the existing electrochemical conditions: Eh measurements indicate reducing conditions in the top 6 cm of the core and oxidizing conditions in the lower sections. Generally when manganese oxides are in a reducing environment, a lowering in the oxidation state of the metal will occur. With Mn, the lower the oxidation state, the greater its solubility in water and thus the greater its mobility[6]. Under reducing conditions, Mn will be lost from the sediment to the water (this is verified by the water analysis results, Table 3). At the lower sections of the core, less reducing conditions prevail which maintain the higher oxidation states of Mn, thereby stabilizing the metal in the sediment. Thus, higher levels are observed at lower depths.

While the Al profile (Figure 2(e)) is similar to that of Mn, the reason for the increase in the metal concentration with sediment depth is different. Al levels steadily increased over the 0-6 cm depth range to the background level of approximately 31000 μg/g. The lower Al concentration in the top sediment sections may be attributed to the enrichment of organic materials and debris resulting from land clearing for mining purposes, as these materials contain significantly less Al than do the clays which predominate in the background.

Relatively low levels of both Ni (Figure 2(c)) and Cr (Figure 2(f)) were found in the sediments. The Ni profile is similar to those of Cu, Zn and Fe with the metal enrichment point occurring at approximately the 5 cm depth. The maximum Ni level was 103 μg/g with the background level being 55 μg/g. The Cr concentration profile, however, exhibits rather erratic behaviour. The minimum Cr level of 39 μg/g is found in the 2-3 cm section with the maximum level of 98 μg/g at 5-6 cm. This type of Cr behaviour was not observed in any of the other lakes with the exception of Lac Dufault. Possible reasons for such a fluctuation in the metal level might include changes in the operational technology of the mining/smelting industry as well as modifications in the treatment of waste materials prior to their disposal. Otherwise, no specific pattern can be established from the Cr profile.

Carbon analysis was performed on the sediment sections to estimate the total organic (TOC) and total inorganic (TIC) carbon content (Figure 2(g)). Total carbon content increased steadily from a 2% background level to 6.7% in the surface layer. This increase was due primarily to organic carbon, with the overall 4.7% difference estimated to be 4.3% organic carbon and 0.4% inorganic carbon. The increase in the total carbon level coincides with the advent of mining in the area (1926). This is supported by the pollen dating results. Water runoff from the mines may have carried minerals enriched with nutrients such as phosphorus and its related compounds. The nutrients would provide an ample source for the growth of benthic communities in the lake. Coupled with the mining industry would be an increase in the human population of the area, thereby increasing the amount of waste discharges and thus the levels of organic carbon. Furthermore, the increase in organic carbon and heavy metal levels in the 6-7 cm sections, upon back-projection, would coincide with the start of the mining industry in 1926.

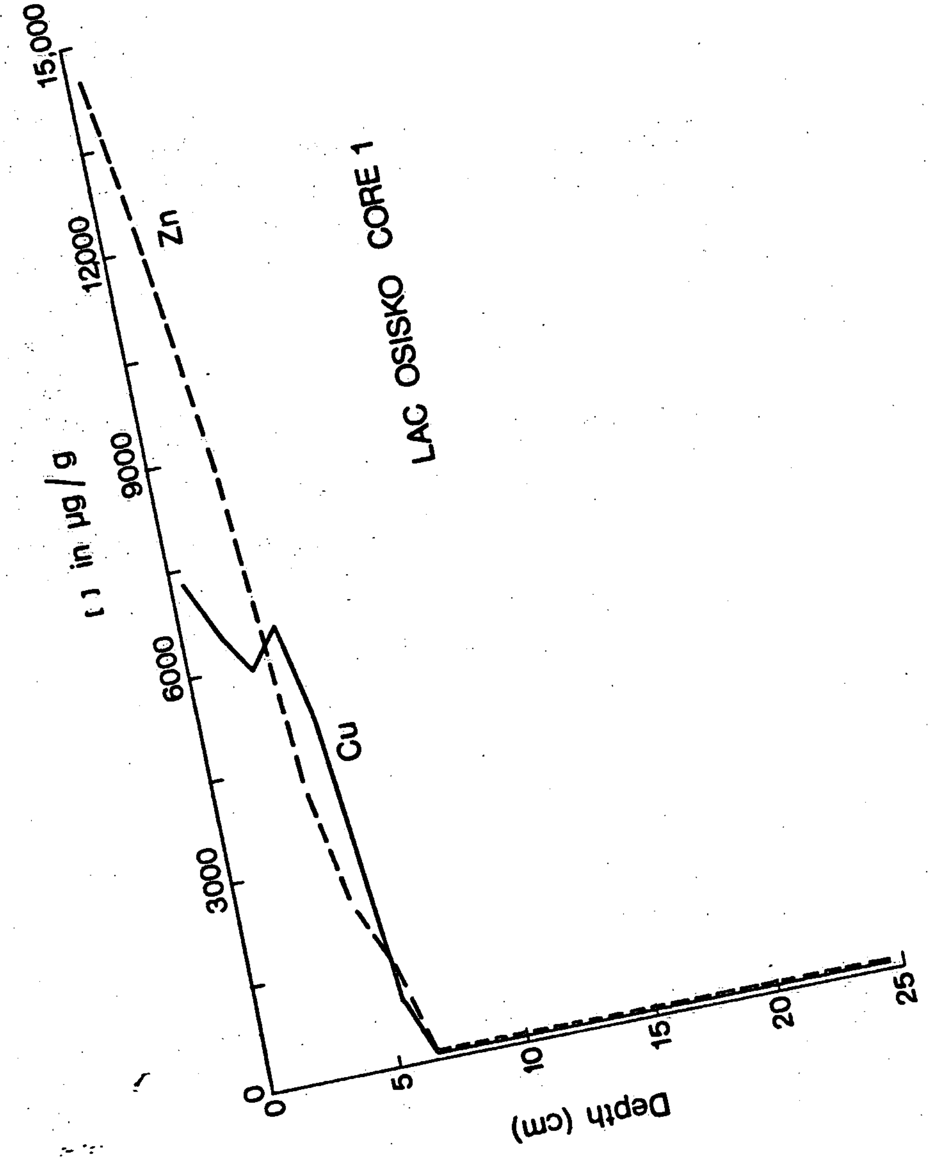


Figure 2(a). Distribution of Cu with Sediment Depth

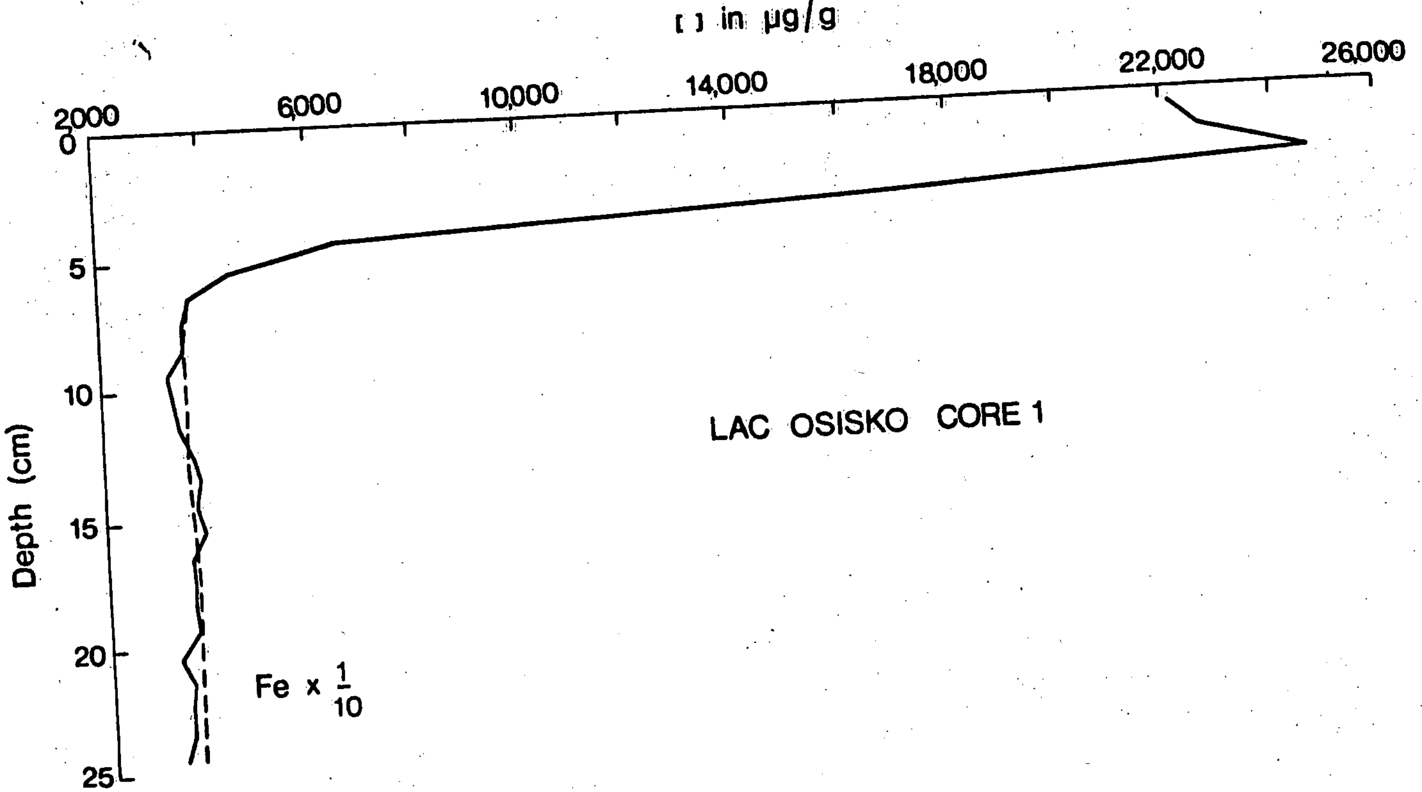


Figure 2(b). Distribution of Fe with Sediment Depth

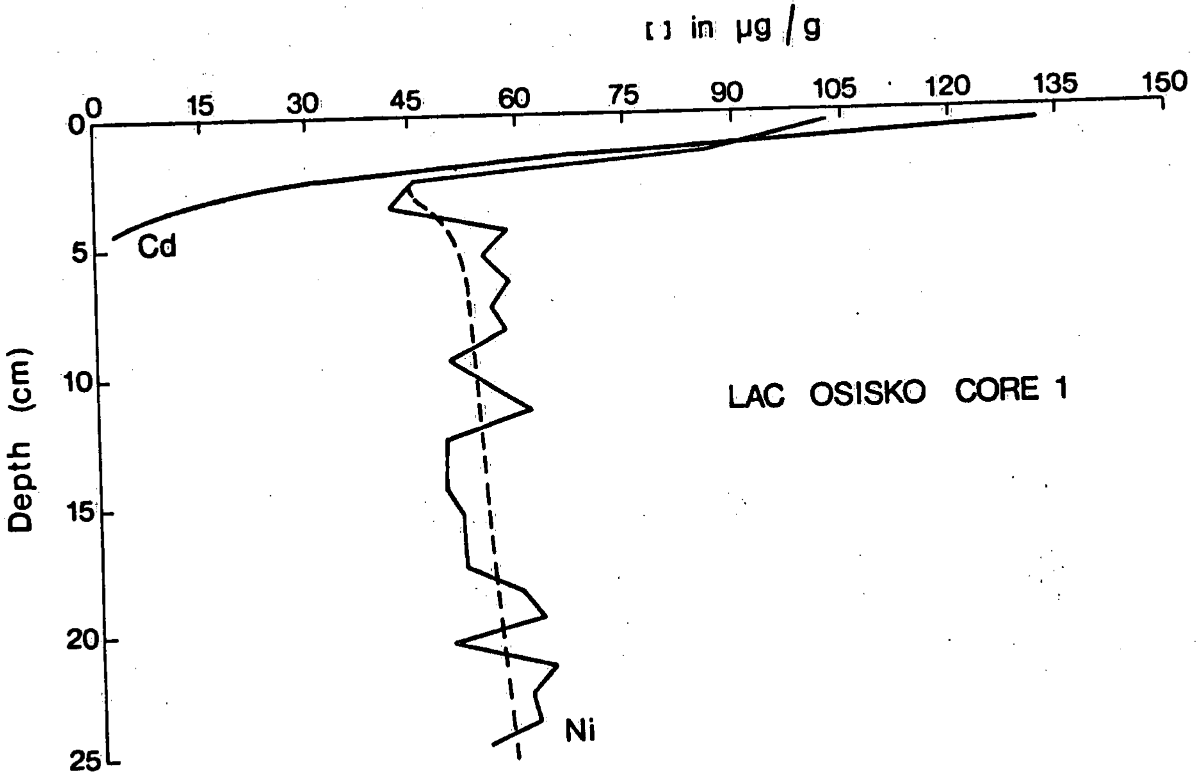


Figure 2(c). Distribution of Ni and Cd with Sediment Depth

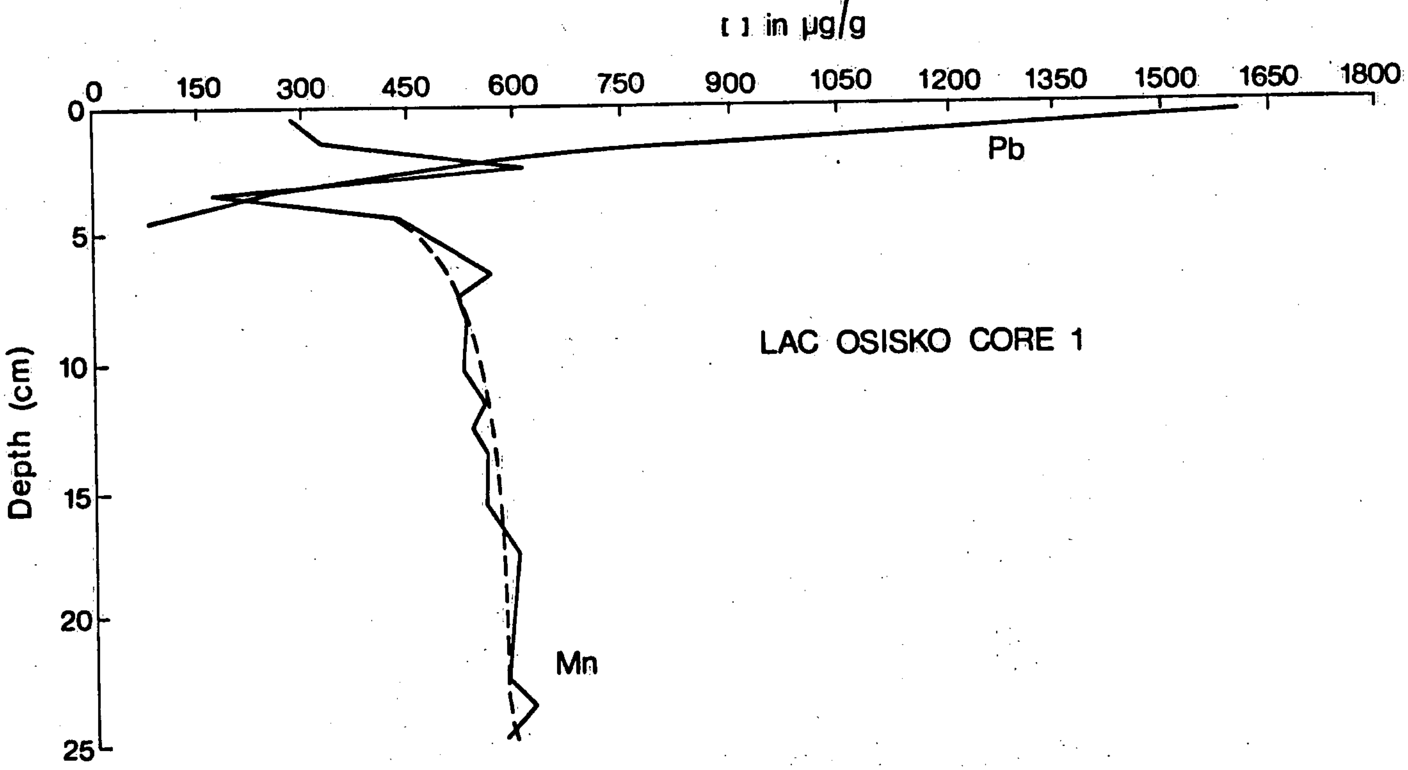


Figure 2(d). Distribution of Mn and Pb with Sediment Depth

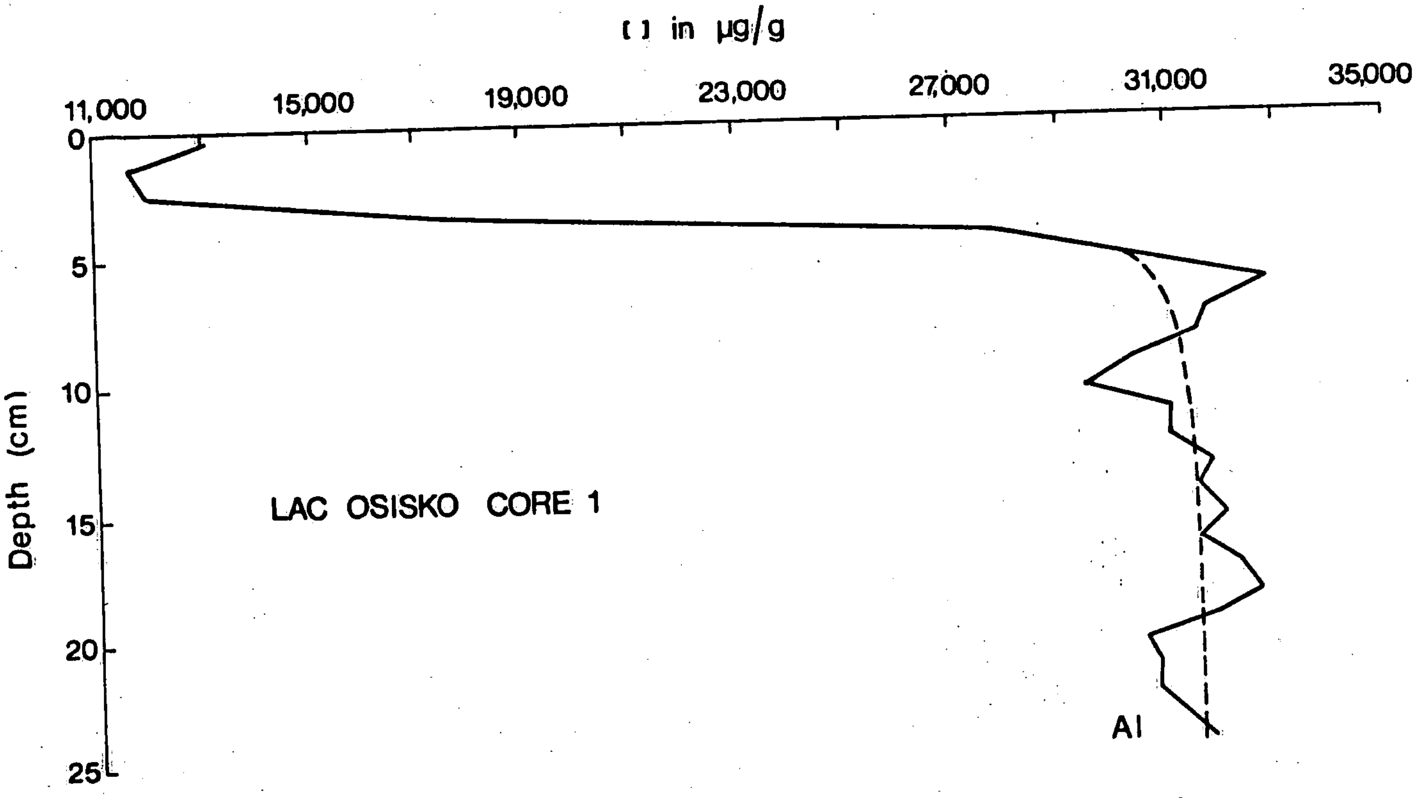


Figure 2(e). Distribution of Al with Sediment Depth

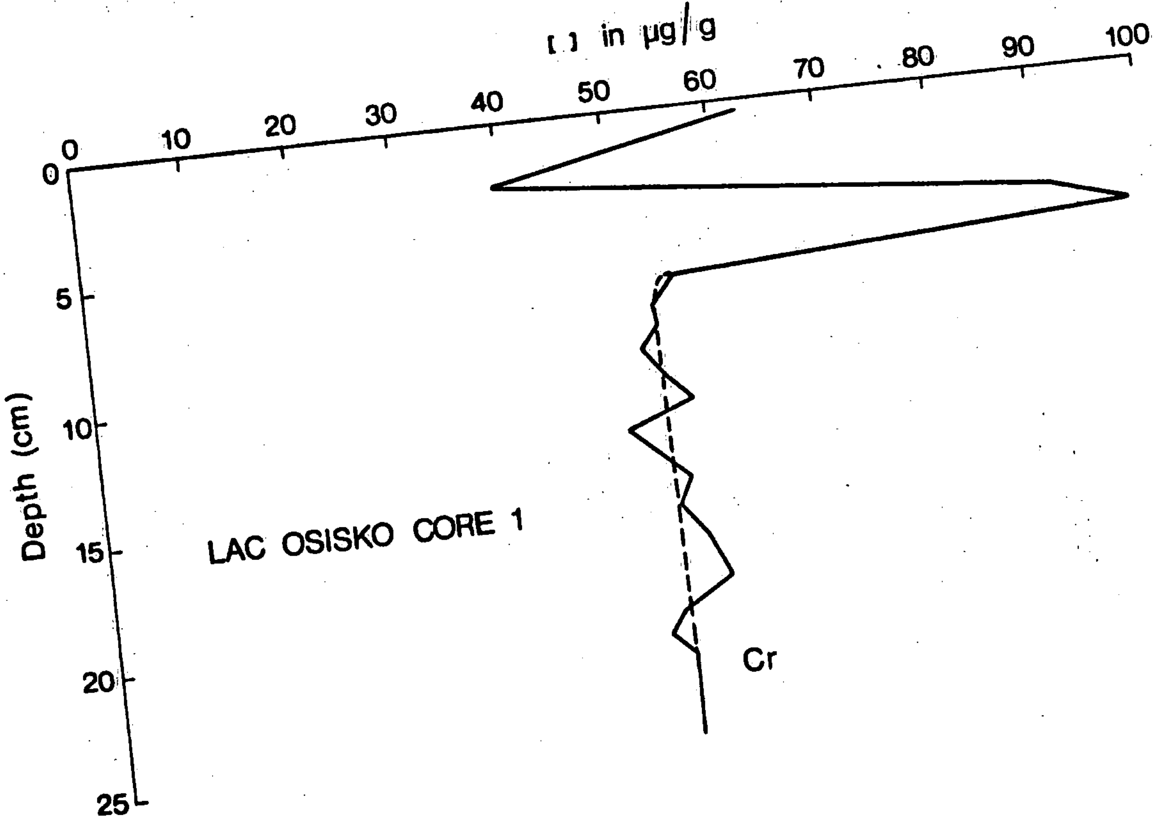
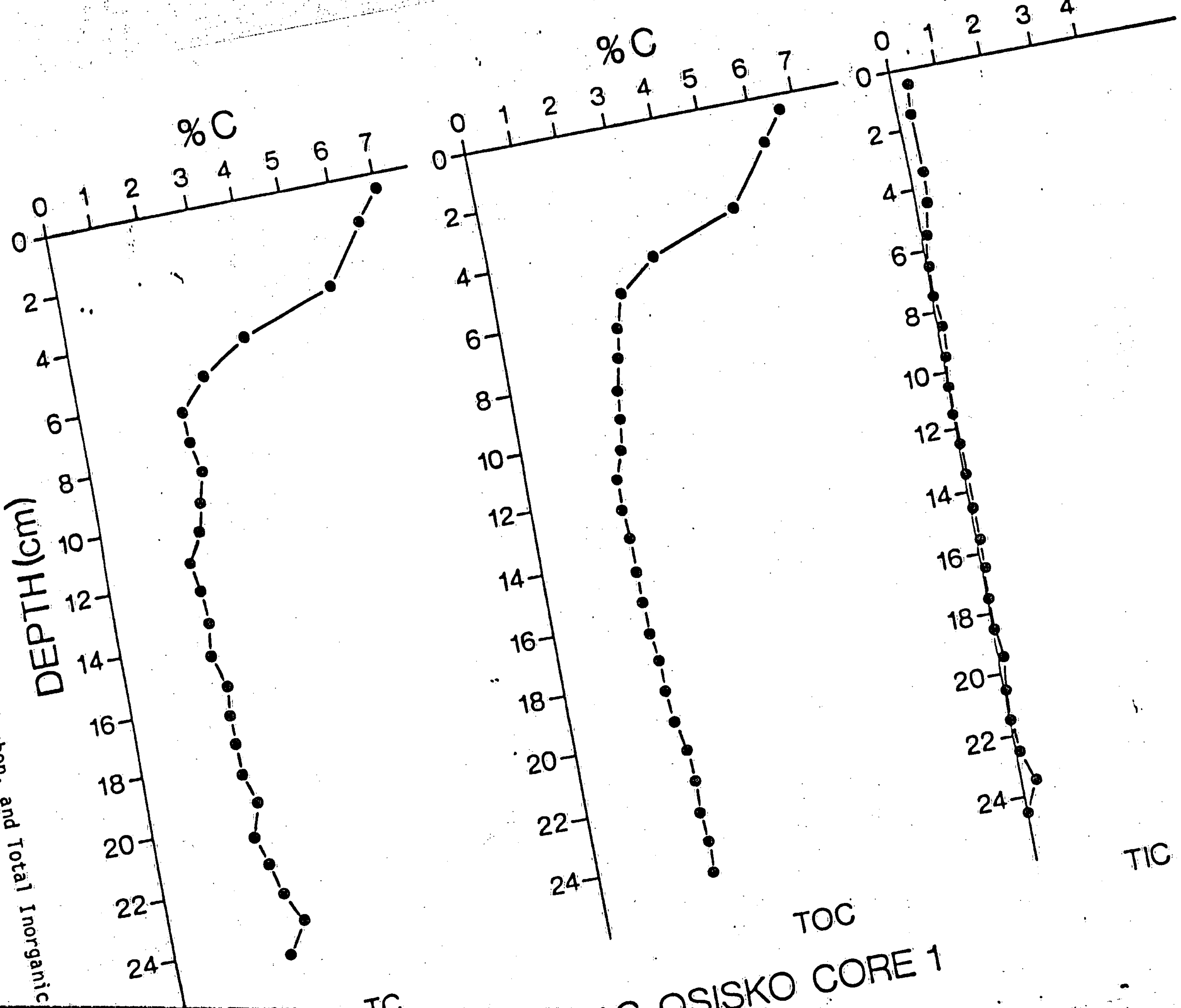


Figure 2(f). Distribution of Cr with Sediment Depth



Total Organic Carbon, and Total Inorganic
ith Sediment Depth.

Lac Dufault

Lac Dufault is located approximately 8 km NNE from the Noranda stacks at 48°18'N, 79°01'E. Abandoned mine shafts as well as mine-tailing ponds are located within 2 km of the lake.

Two cores were obtained: Core 1 (C1), was taken from a depth of 8 m with the EBT profile showing isothermal conditions in the water column. Eh measurements indicated oxidizing conditions throughout the core, with a surface Eh of +150 mV and pH 7.2. The second core, C2, was taken from a depth of 15 m with the EBT profile indicating stratified conditions in the water column. Here again, oxidizing conditions prevailed throughout the core, with the surface layer having an Eh of +160 mV and a pH of 6.9.

Of the two cores, Core 2 (C2) may be the more representative. In general, deeper parts of a lake are less likely to be disturbed and thus are better accumulators of particles. Furthermore, the near neutral sediment pH levels reduce the possibility of metals leaching into the water. (This is supported by the low metal levels found in the water analysis). Shallower portions of the lake bottom are subjected to an increased amount of water motion which may disturb the top few centimeters of sediment, thereby giving incorrect indications of the surface core conditions. Thus, some differences exist between the results of C1 and C2.

Generally, metal enrichment occurs in the 6-8 cm depth range for Cu, Zn, Fe and Pb (Figures 3(a), (b), (c)). The levels of these metals are comparable with those from Lac Osisko. Levels of Mn (Figure 3(c)) are consistent as well with those of Lac Osisko, with the sole difference being the lack of concentration decrease in the surface sediment layer. This is predictable in that no reducing conditions are present as in the previous lake which would allow for aqueous forms of Mn. The Al (Figure 3(b)) profile is similar to that of Lac Osisko as well, with higher organic and debris levels being the cause of the initial low Al levels near the surface. Low levels of both Cr and Ni (Figure 3(d)) were observed, with no specific trends being distinguishable from the profiles.

Carbon analysis yielded data (Figure 3(e)) similar to that from Lac Osisko with increased levels beginning at the 6-8 cm depth, positively deviating from the background 3% level to approximately 9.5% at the surface. Here again, the increase was due mainly to organic carbon.

Enrichment of both metals and organics tends to coincide with the beginning of mining near the lake. Not only is Lac Dufault being contaminanted by the runoff and seepage from the nearby mining operations, but also by the aerial deposition of particles from the Noranda smelter. Of all the lakes studied, Lac Dufault and Lac Osisko are the most comparable, as expected by their proximity to each other as well as similarities in nearby pollution sources.

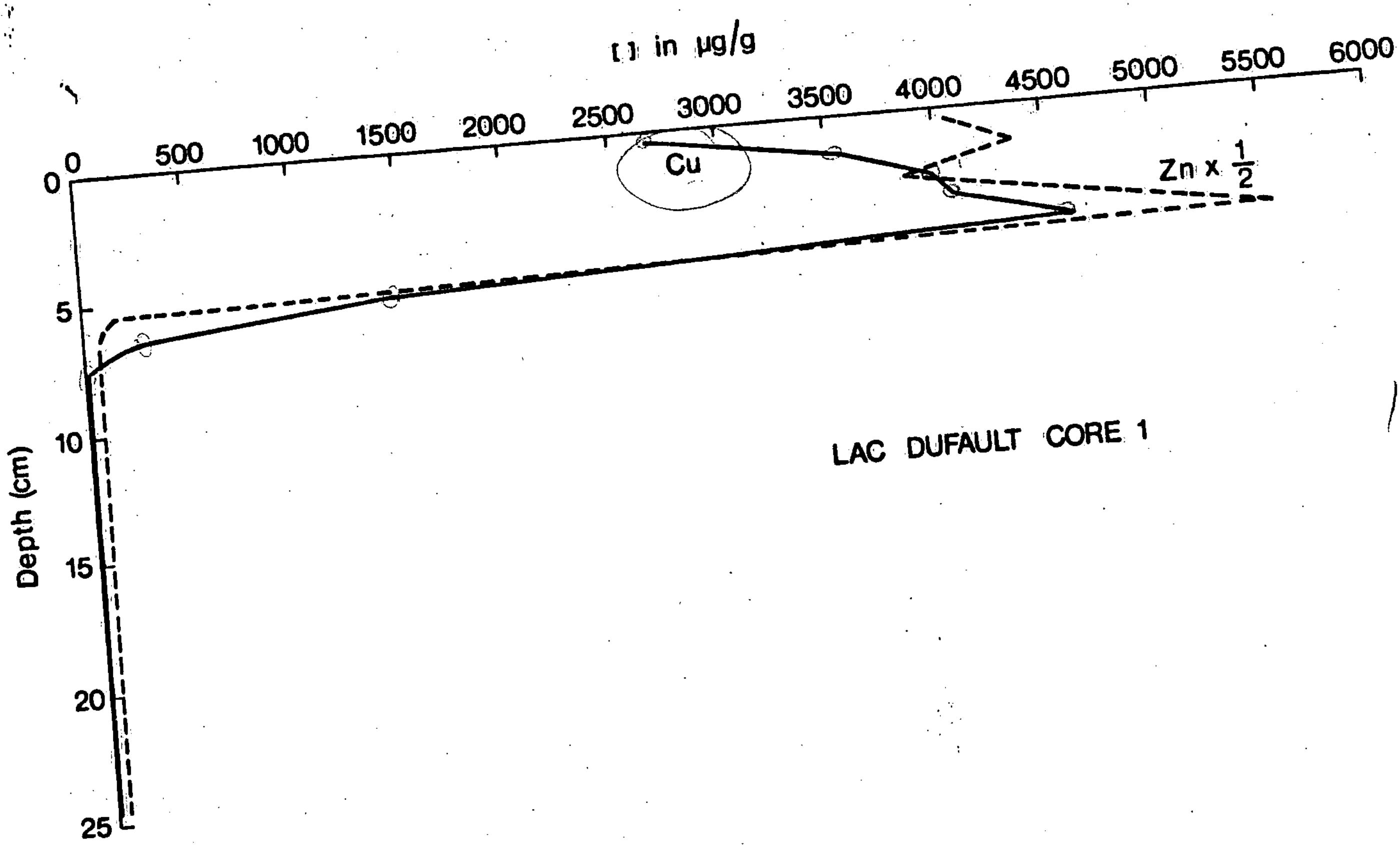


Figure 3(a). Distribution of Cu and Zn with Sediment Depth

1cm sections all the way to 25 cm depth. !

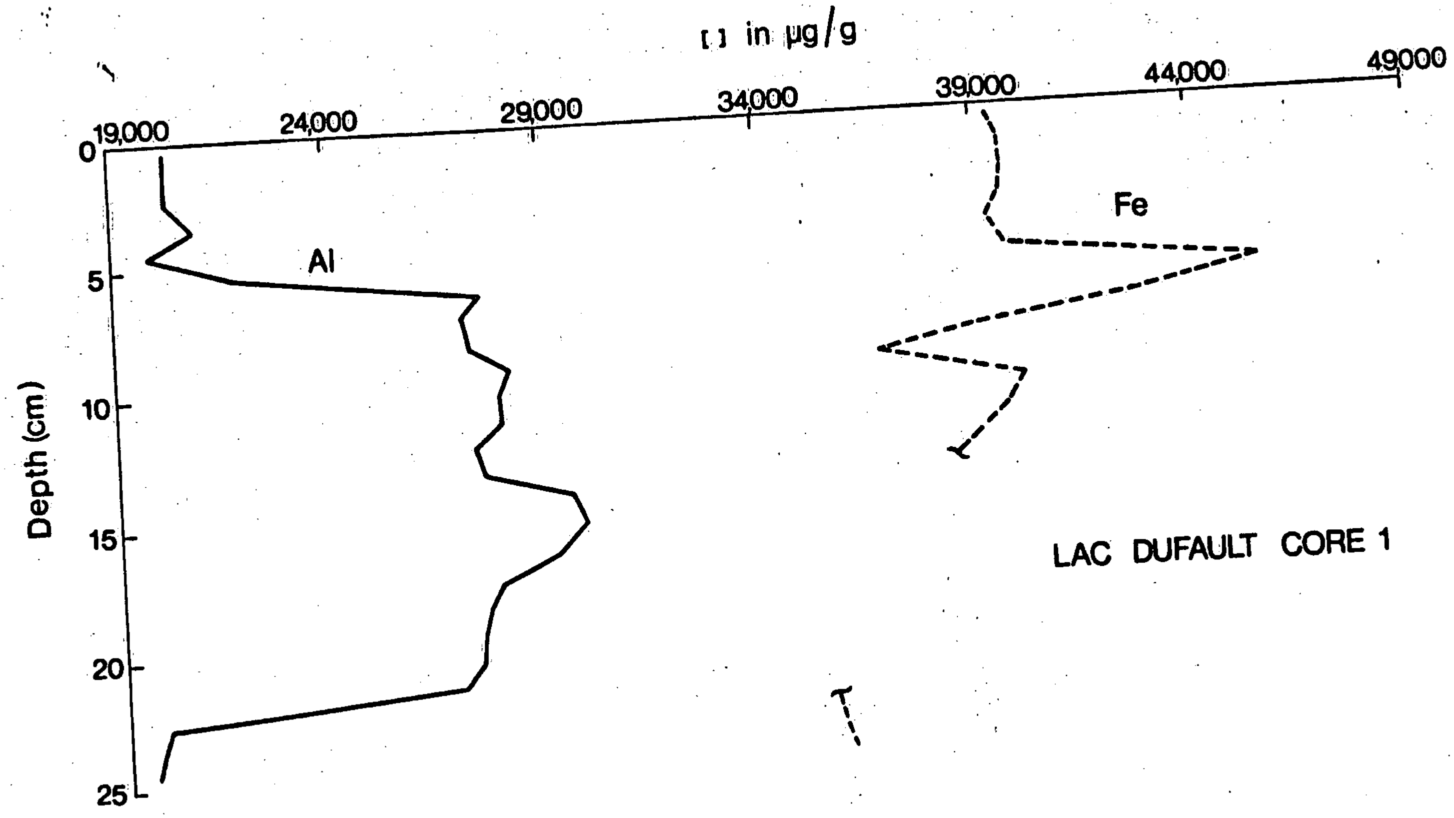


Figure 3(b). Distribution of Fe and Al with Sediment Depth

0-09
10.7

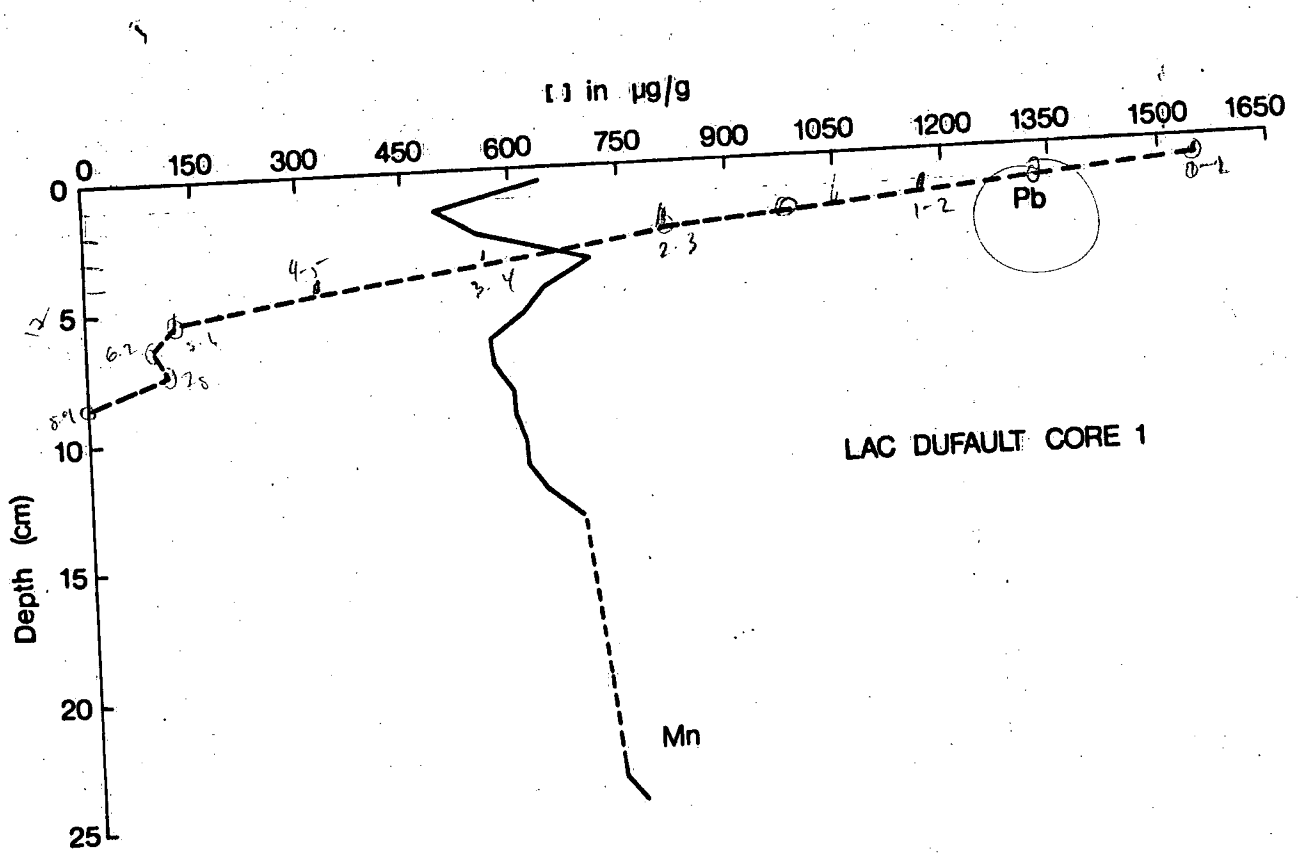


Figure 3(c). Distribution of Pb and Mn with Sediment Depth

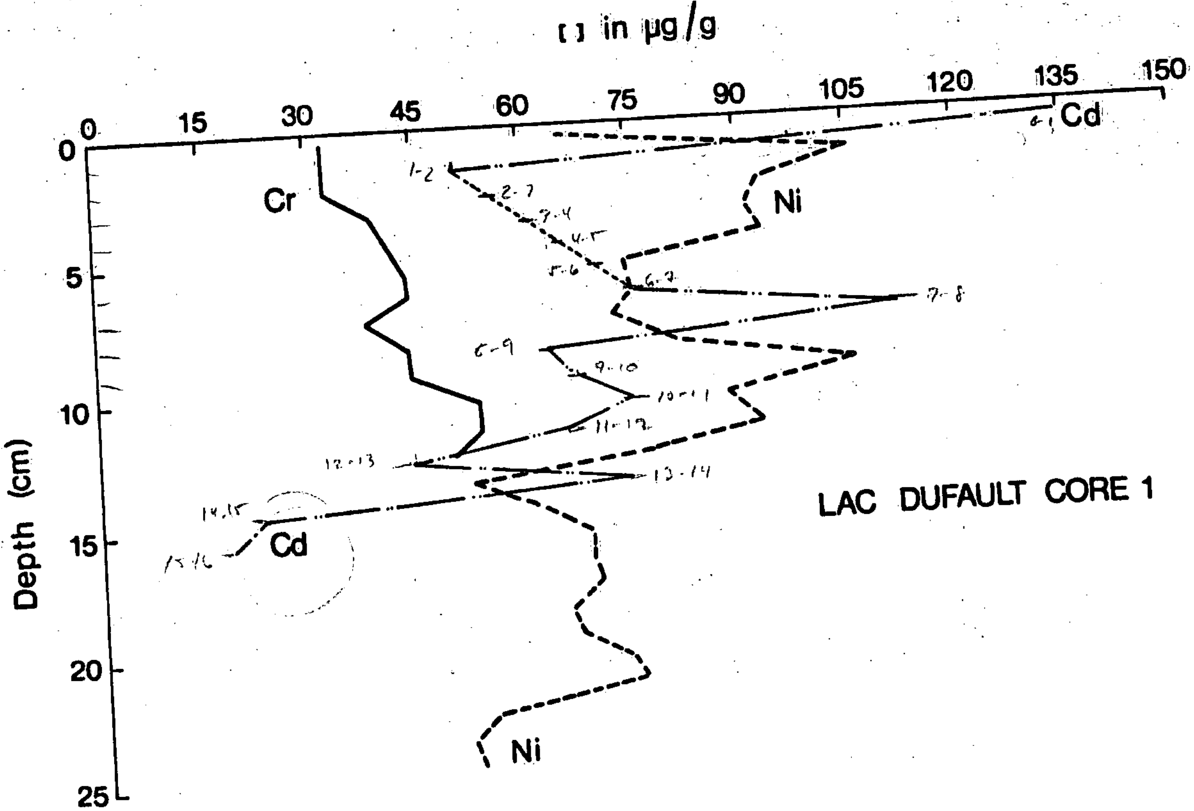


Figure 3(d). Distribution of Ni, Cr, and Cd with Sediment Depth

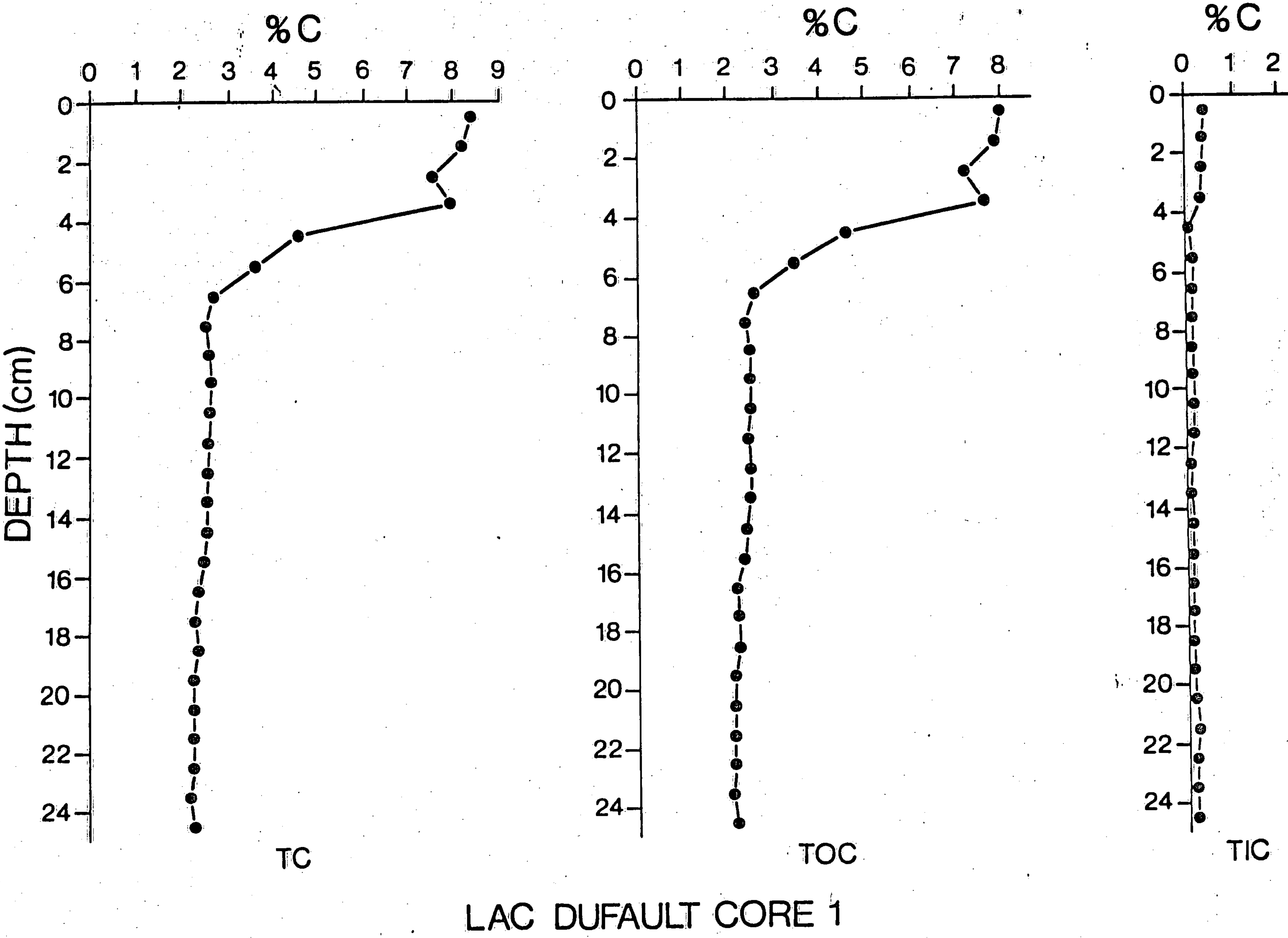


Figure 3(e). Total Carbon, Total Organic Carbon, and Total Inorganic Carbon Distributions with Sediment Depth

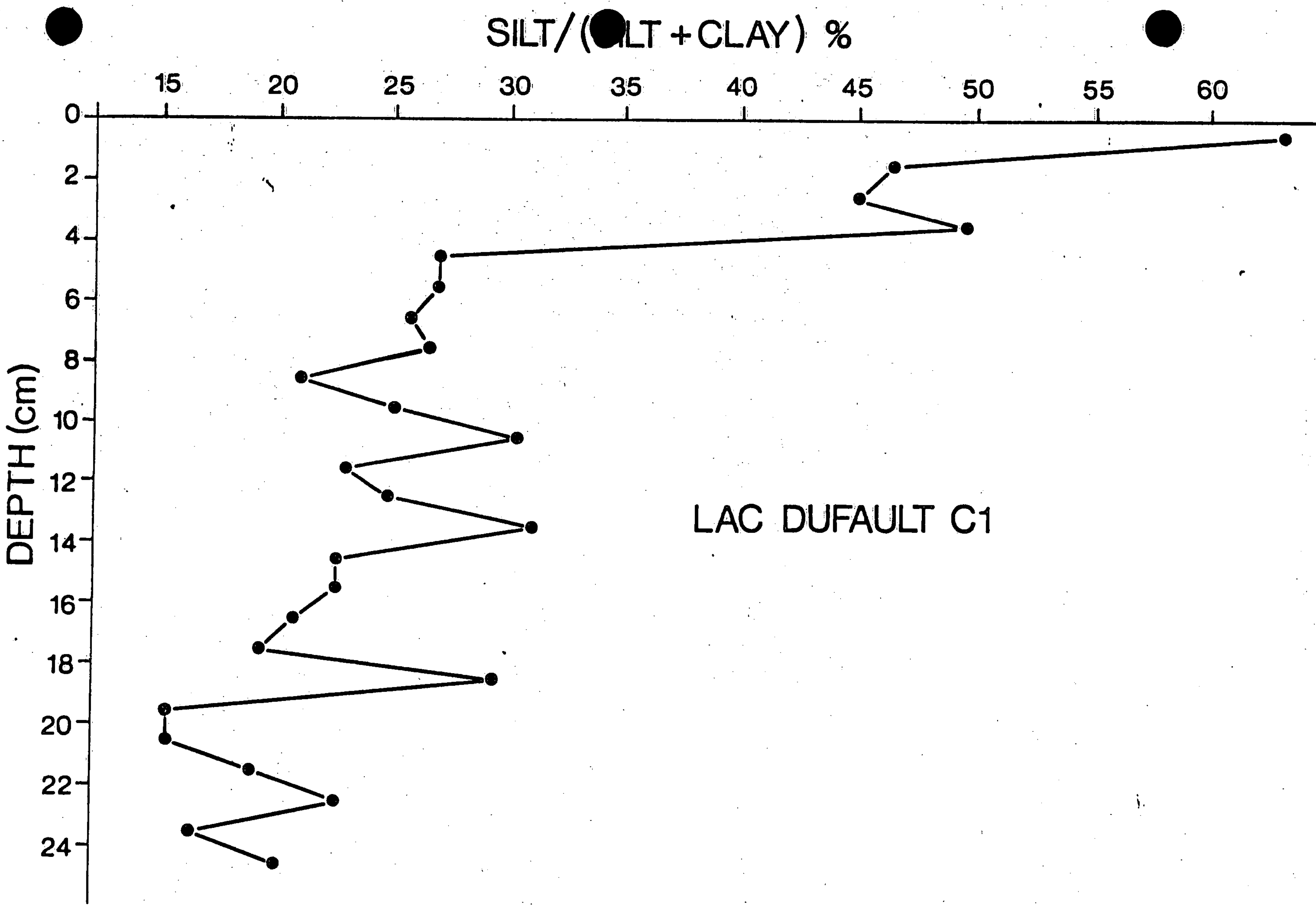


Figure 3(f). Distribution of Silt/(Silt + Clay) with Sediment Depth

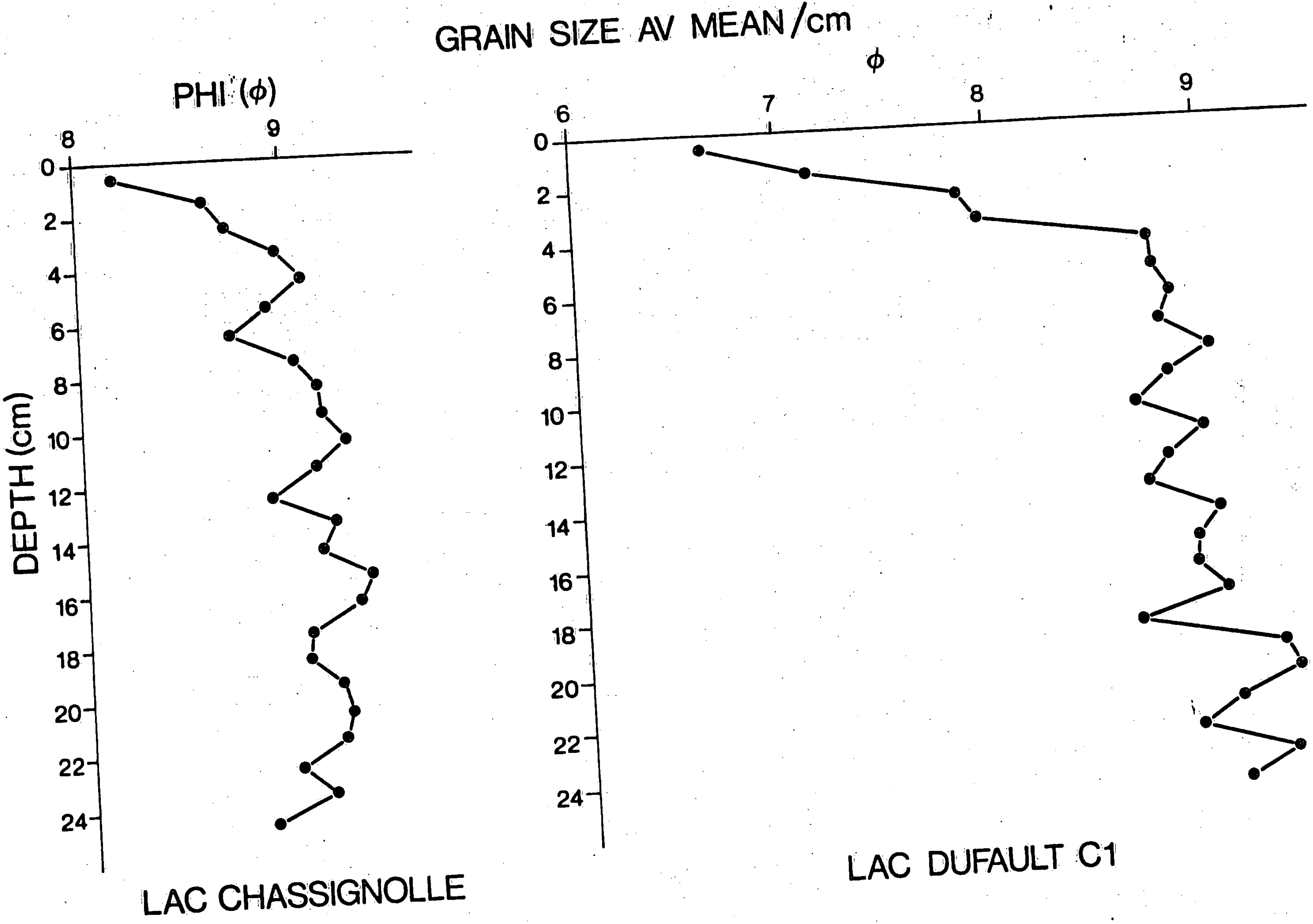


Figure 3(g). Distribution of Grain Size with Sediment Depth

Lac Duparquet

Lac Duparquet is located approximately 35 km NW of the Noranda smelter at 48°29'N, 79°17'E. The core was obtained from a depth of 7 m with the EBT profile indicating slightly stratified temperature conditions in the water column. Eh measurements indicated oxidizing conditions throughout the core, with a surface Eh of +370 mV and pH 6.6.

The Beattie gold mine and smelter are located on the northern shore of the lake. The mine was operational until 1953. Presently, the smelter is used to process molybdenum.

The metal profiles indicate increasing levels of Cu, Fe, Zn, Mn, and Pb (Figures 4(a), (b), (c), (d)) in the top 8 cm with enrichment occurring in the range 6-8 cm. Compared to ~~Lakes~~ lakes Osisko and Dufault, the levels of Fe, Cu and Zn are significantly lower. The increased levels of Pb can be attributed to atmospheric deposition. The elevated level of Mn in the surface layer could be a result of the molybdenum processing since the plant is located on the shores of the lake. Al, Cr and Ni (Figures 4(a), (b), (d)) behave as in other regional lakes. Traces of Mo (Figure 4(d)) were found to a depth of 6 cm with an average of 24 μg/g. Our results for Cu, Pb, Zn, Ni, Cd, and Mn compared well with those obtained from an earlier Quebec study by Sloterdijk and Azzaria (1979)[7] on Lac Duparquet using grab samples:

	Metal					
Study	Cu ppm	Pb ppm	Zn ppm	Ni ppm	Cd ppm	Mn ppm
Quebec	63	56	200	45	3	1840
A.E.D.	84	58	222	49	1	1571

Carbon analysis (Figures 4(e) (f)) indicated fairly steady levels of TOC (2%) and TIC (0.1%), suggesting no substantial organic influx into the area during the mining period.

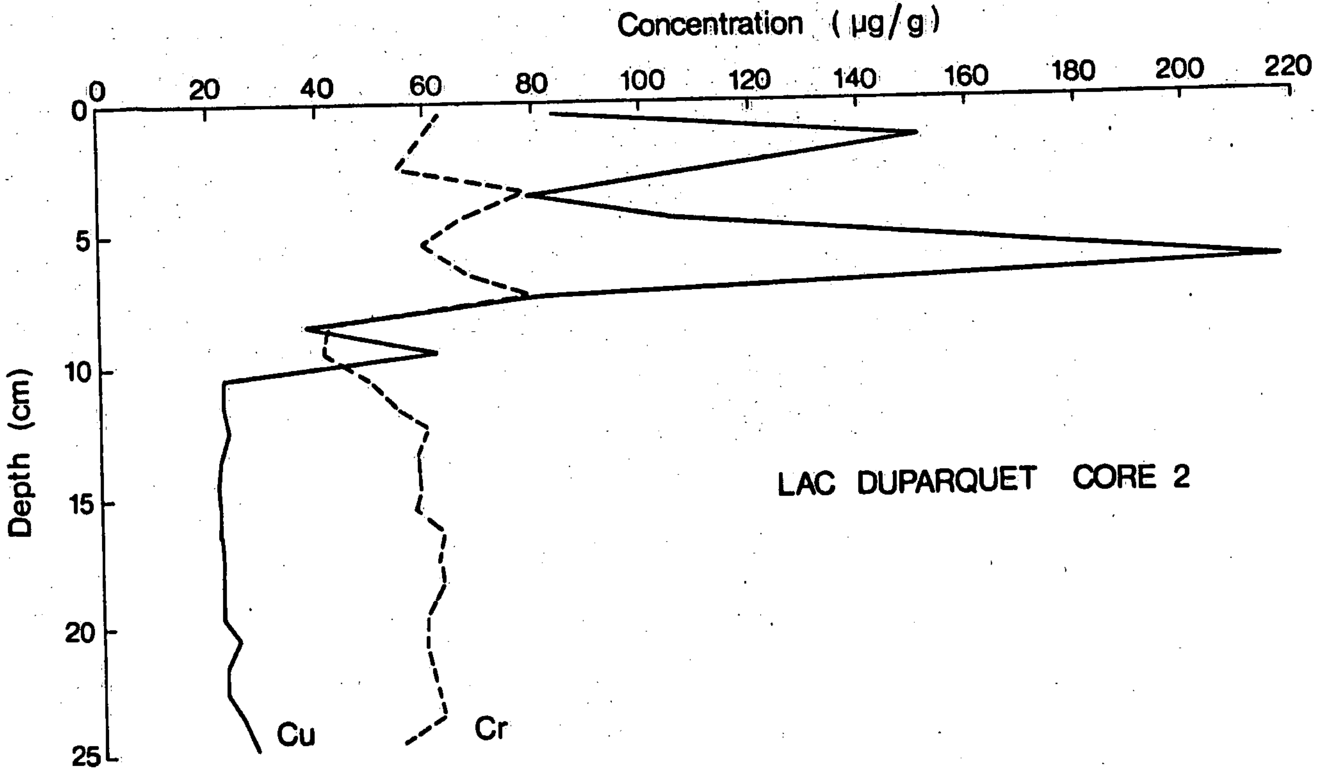


Figure 4(a). Distribution of Cu and Cr with Sediment Depth

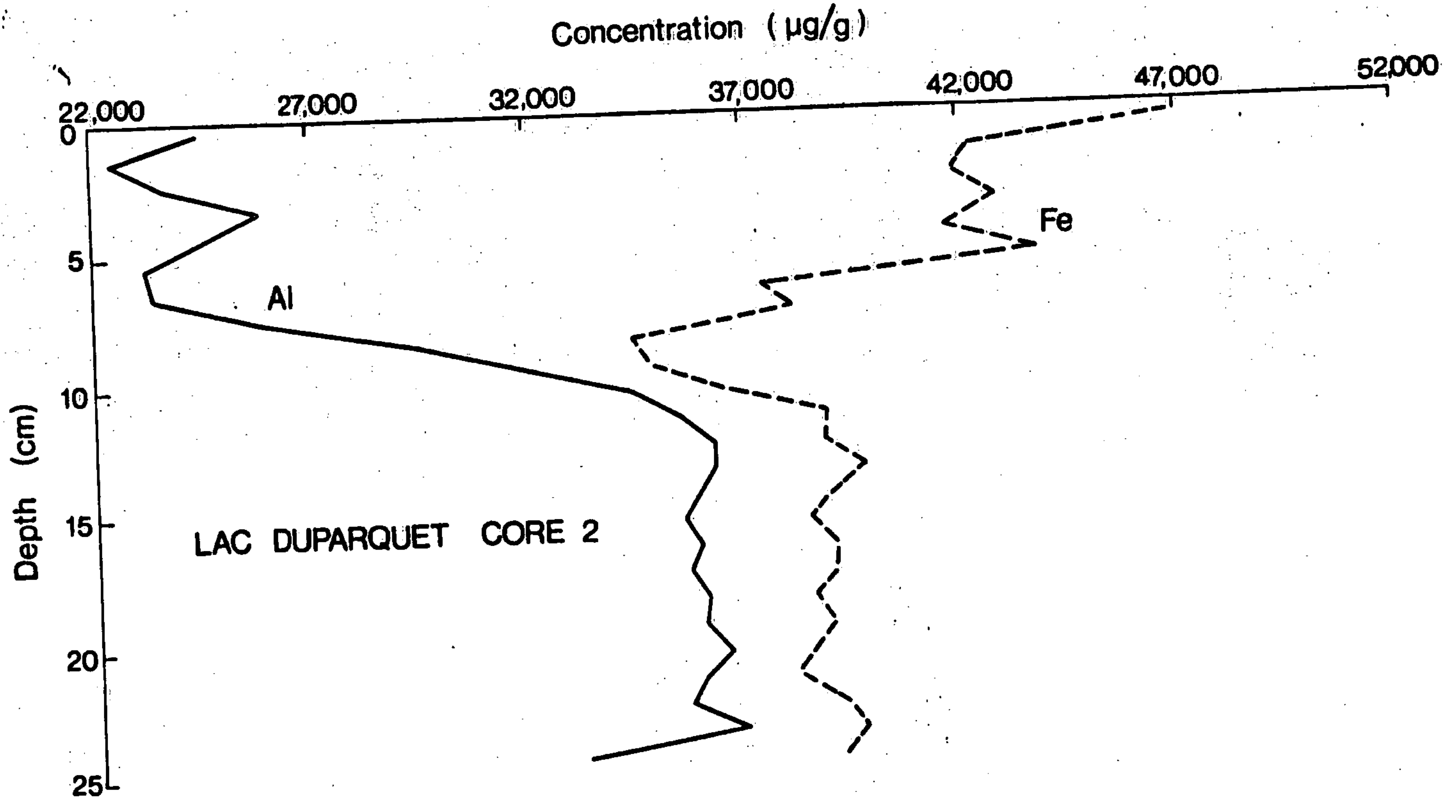


Figure 4(b). Distribution of Fe and Al with Sediment Depth

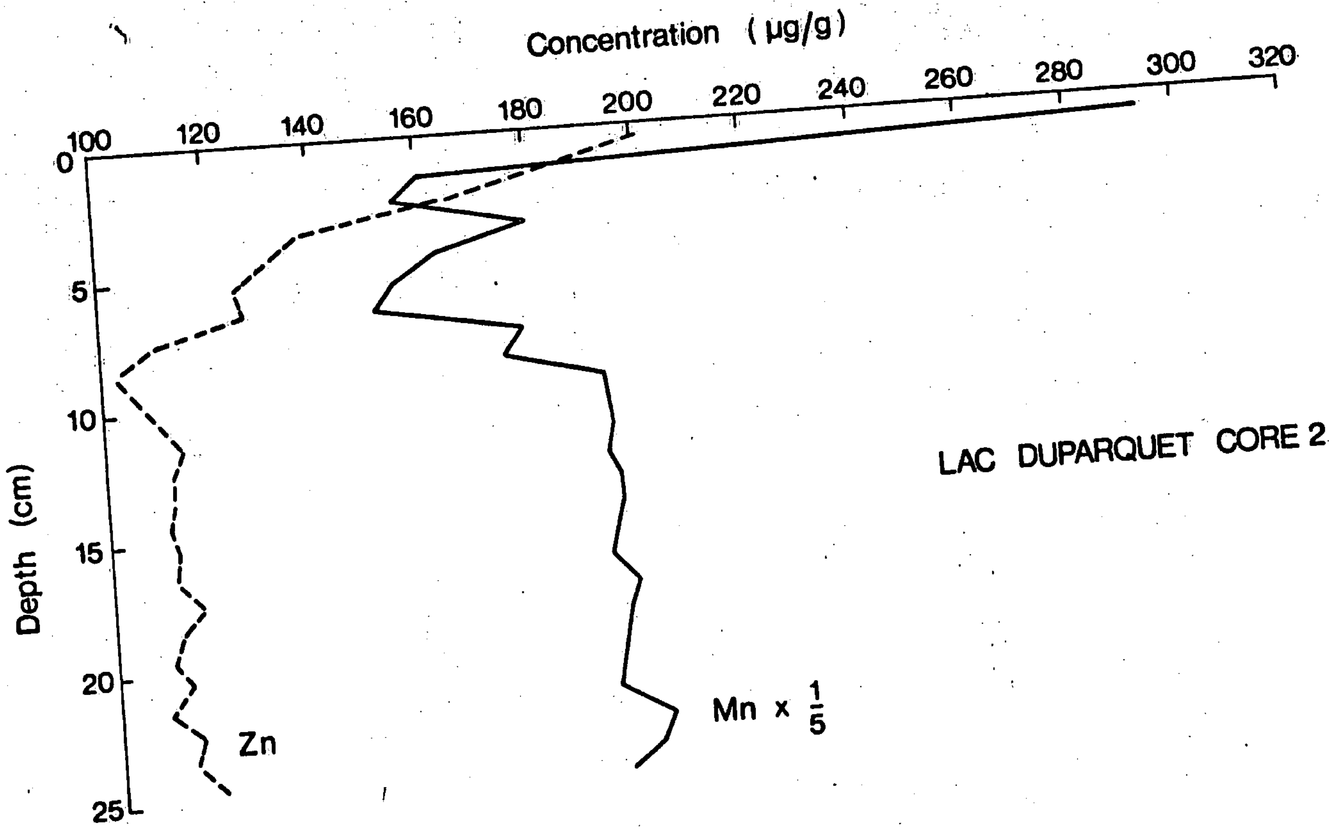


Figure 4(c). Distribution of Zn and Mn with Sediment Depth

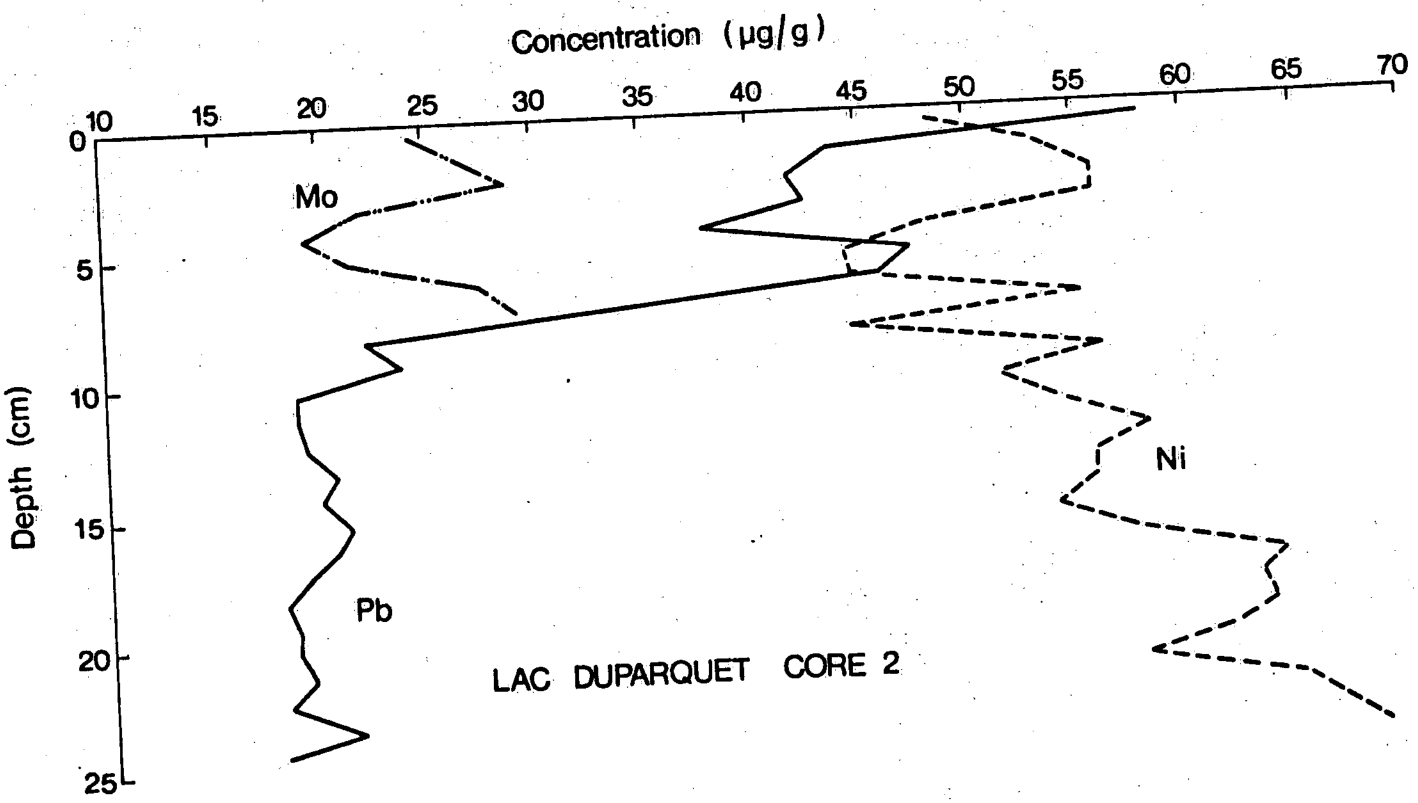


Figure 4(d). Distribution of Ni, Mo, and Pb with Sediment Depth

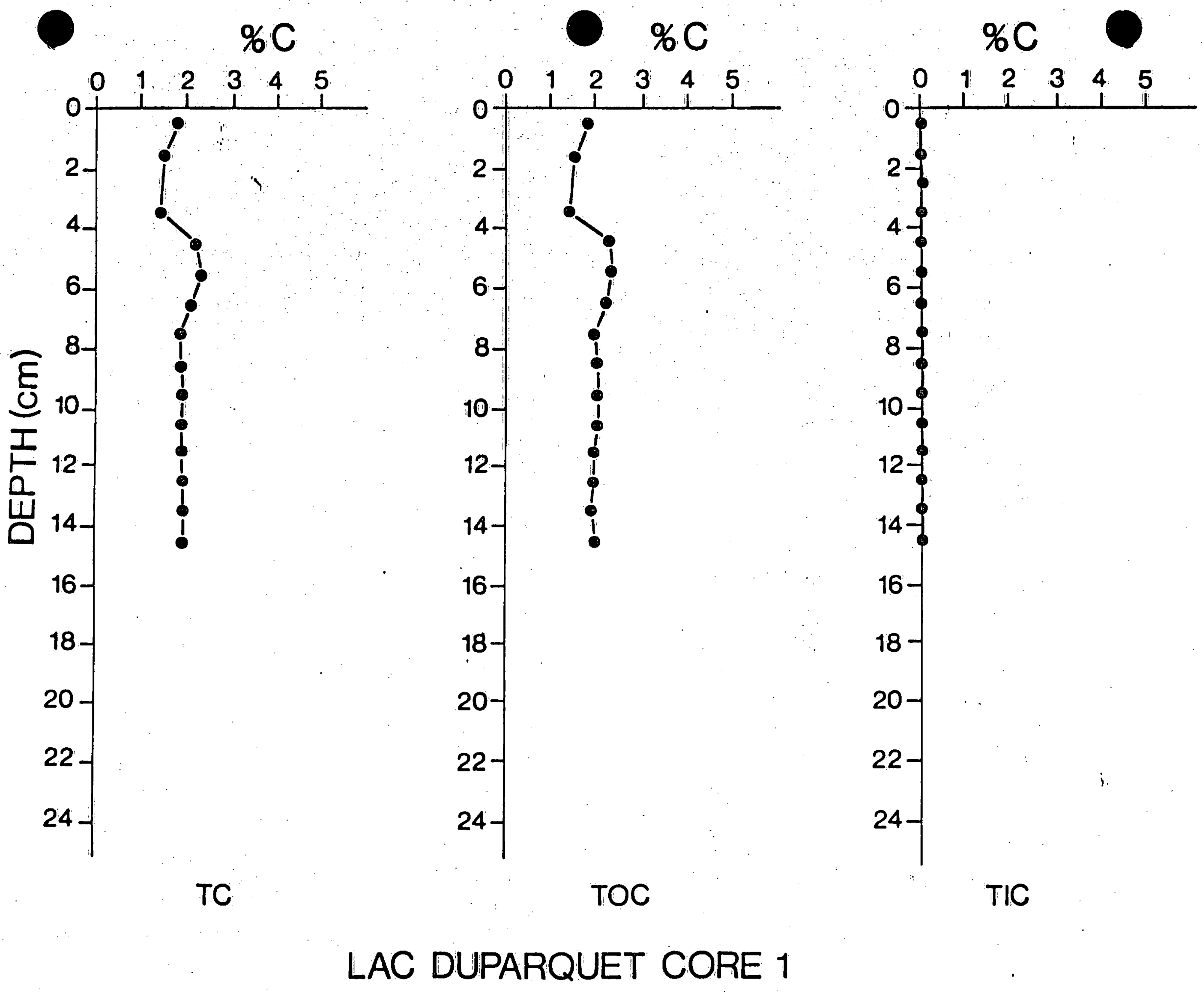


Figure 4(e). Total Carbon, Total Organic Carbon, and Total Inorganic Carbon Distributions with Sediment Depth

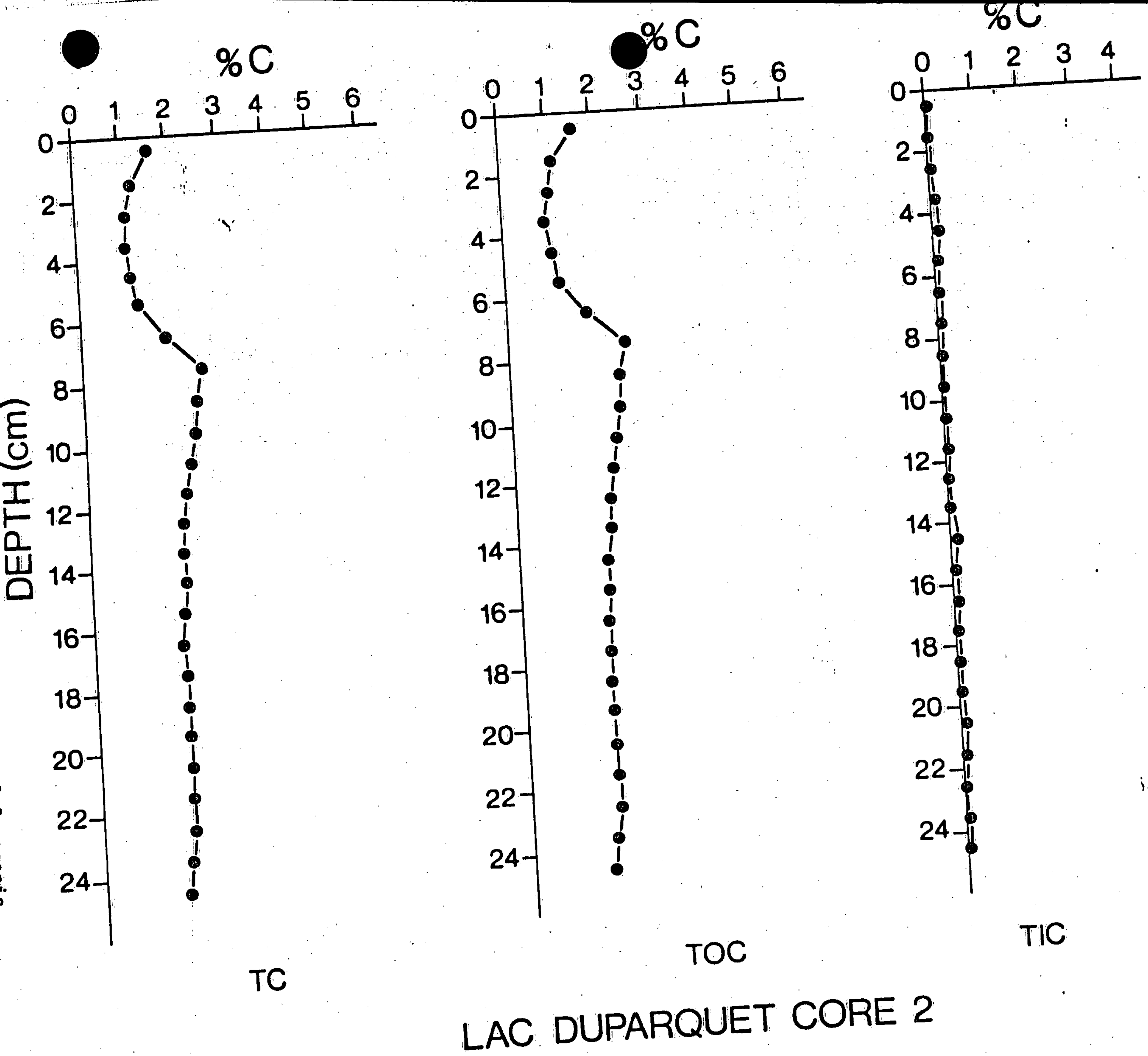


Figure 4(f). Total Carbon, Total Organic Carbon, and Total Inorganic Carbon Distributions with Sediment Depth

Lac Macamic

Lac Macamic is located approximately 60 km north of the smelter at Noranda at 48°47,N, 79°00'E. The core was obtained from a depth of 2 m. The lake was shallow throughout, and on the day of sampling, conditions were such that the top sediment layer was disturbed, resulting in a light brown colored water, with elevated levels of Al and Fe. Oxidizing conditions were prevalent throughout the core with a surface Eh of +315 mV and sediment pH of 6.4.

The metal profiles (Figures 5(a) (b)) indicate stable levels throughout the core which are substantially lower than those of the other lakes studied. This is not surprising in that Lac Macamic is the furthest in distance from the smelter of the lakes studied as well as being isolated from contaminant sources such as mine tailing ponds. Constant levels of carbon (Figure 5(c)) were also observed. Thus, this lake can be used primarily as an indicator of the background levels of the chemical species which we were measuring, primarily because its mineralogy is comparable with that of the other lakes studied (see Table 5).

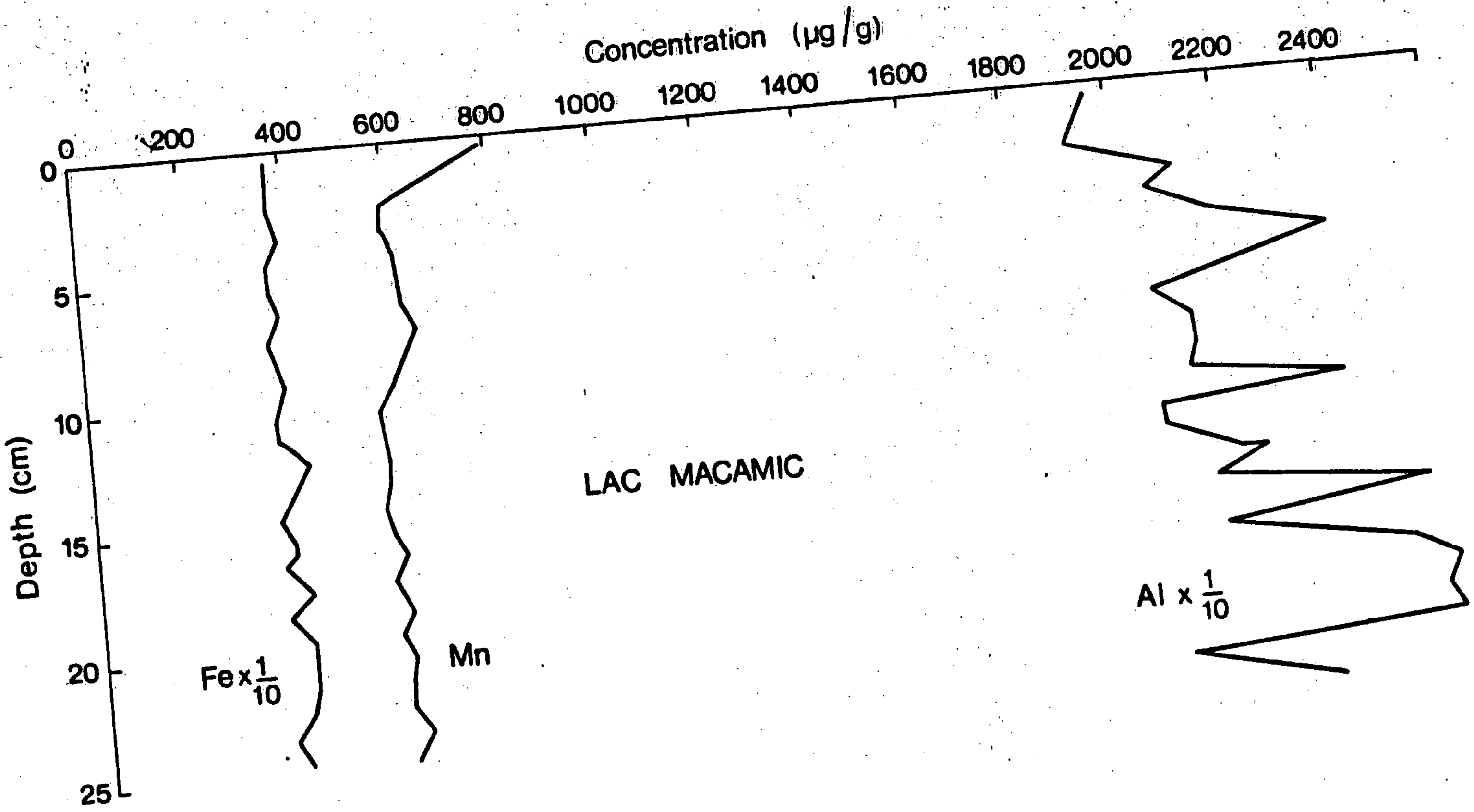


Figure 5(a). Distribution of Fe, Mn, and Al with Sediment Depth

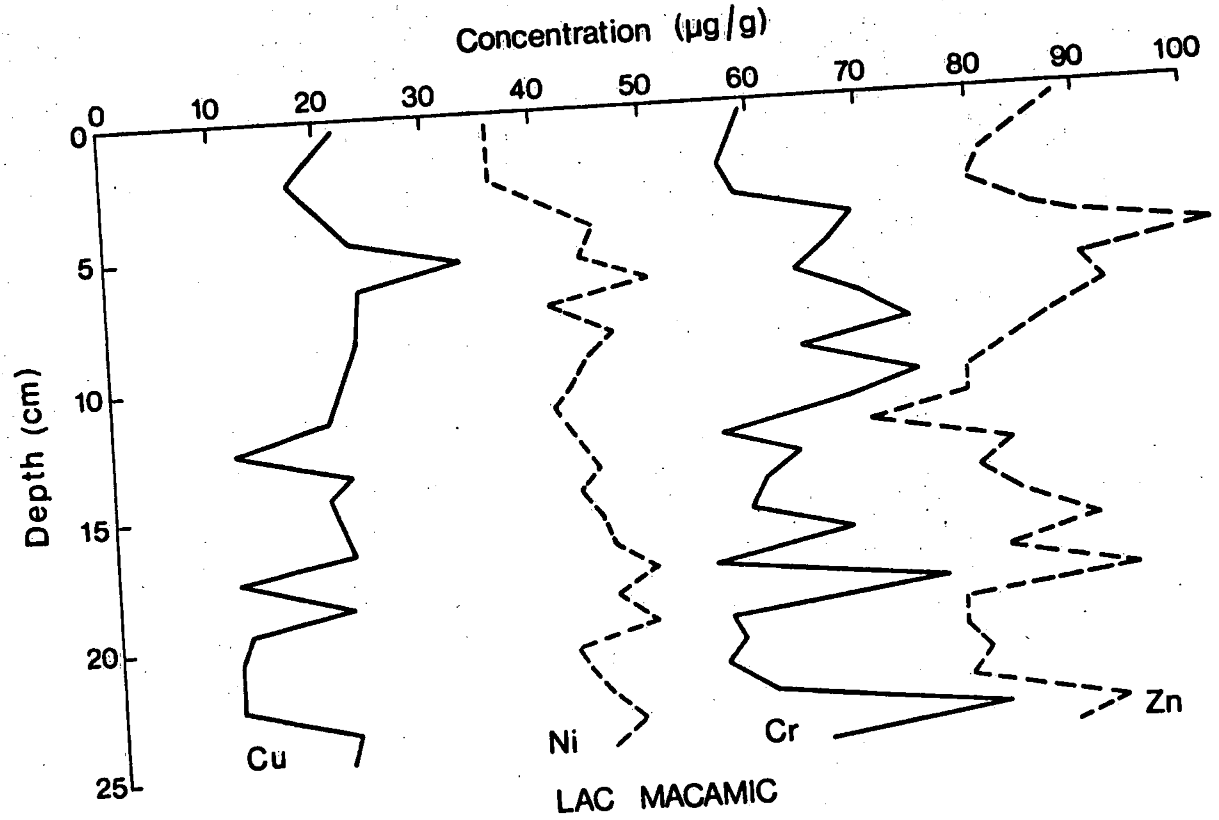
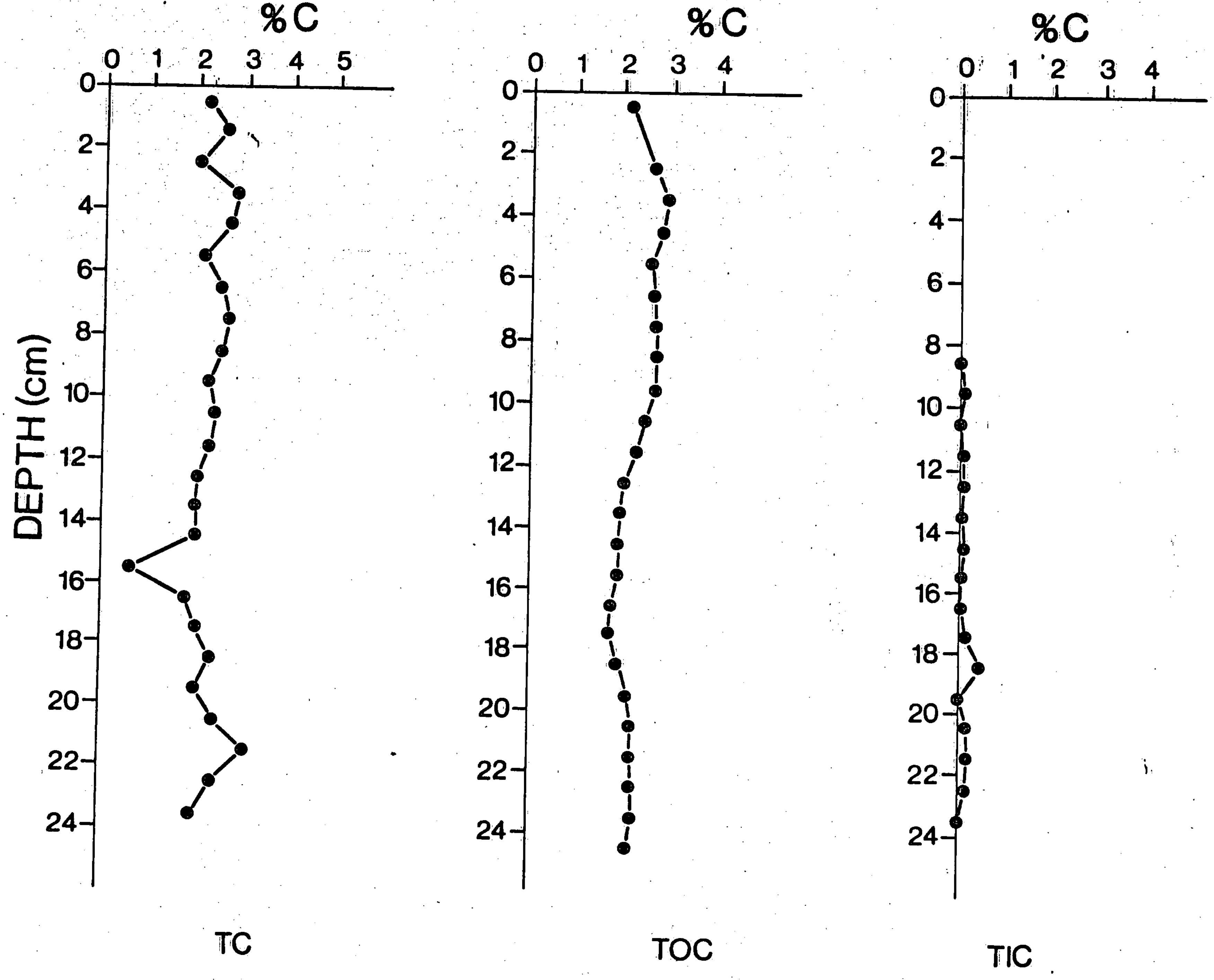


Figure 5(b). Distribution of Cu, Ni, Cr, and Zn with Sediment Depth

Figure 5(c). Total Carbon, Total Organic Carbon, and Total Inorganic Carbon Distributions with Sediment Depth



LAC MACAMIC CORE 1

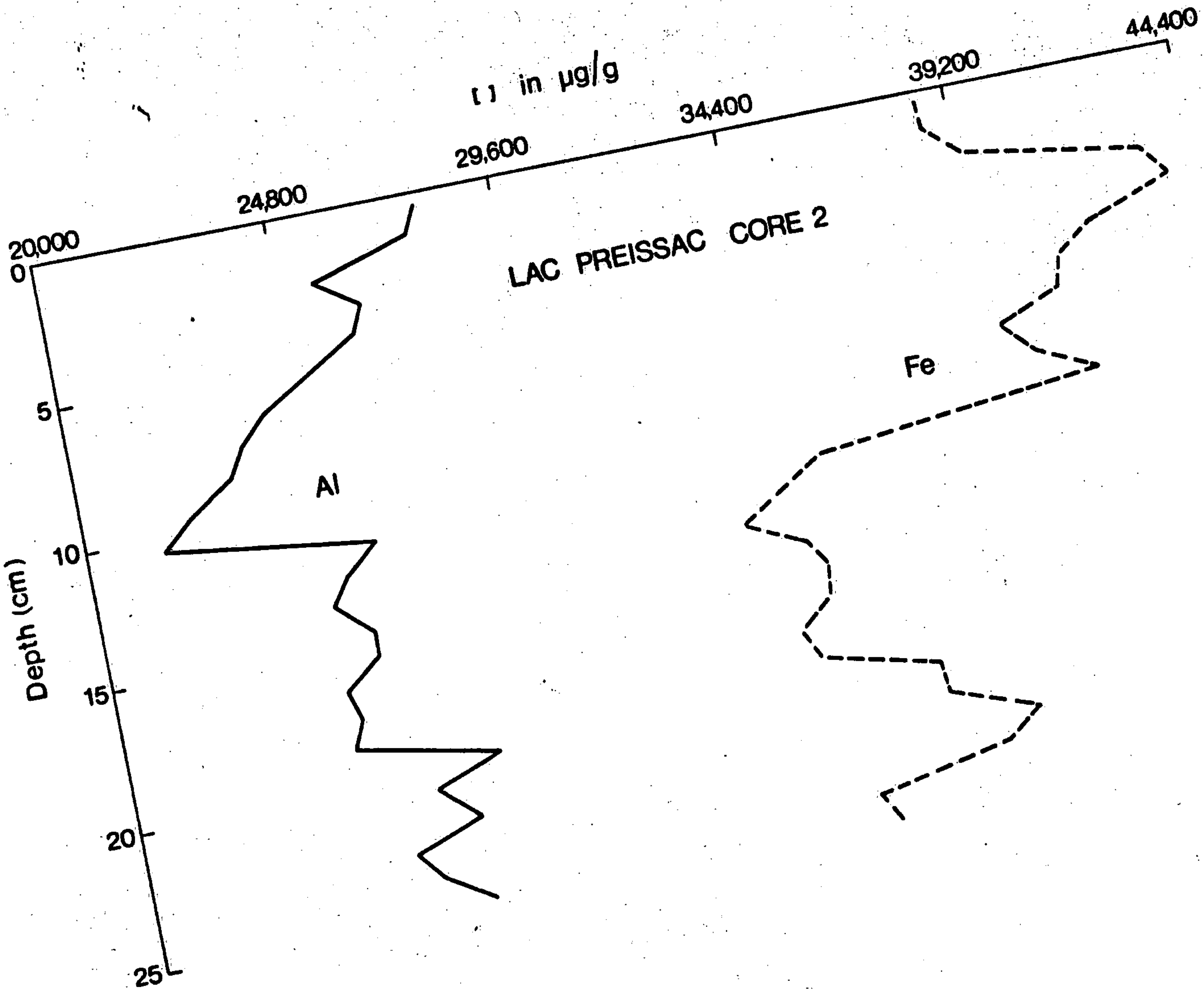
Lac Preissac

Lac Preissac is located approximately 45 km east of the smelter. The most representative core was Core 2 (C2), taken from a depth of 16 m at approximately 48°22,N, 78°20'E. The EBT profile indicated slightly stratified temperature conditions in the water column. Oxidizing conditions prevailed throughout the core, with the surface Eh being +460 mV and pH being 6.9.

Three abandoned mine shafts and three mine dumps are present on the western shores of the lake. Although active mining ceased in the 1950's, seepage from the mine dumps into the lake is probable.

The metal profiles indicate a general enrichment point at the 10 cm depth, with levels of Fe, Zn, Cu, and Pb (Figures 6(a), (b), (c), (d)) increasing steadily nearing the surface. Fe, Zn and Cu levels in the top 10 cm can be attributed to the mining operations nearby; Pb is present for the most part through atmospheric deposition. Compared with Lac Macamic where no such sources of contamination exist, the levels of these metals are noticeably higher. Cr, Ni and Al levels (Figures 6(d), (c), (a)) are comparable with those of other lakes.

No significant variation in the carbon contents (Figures 6(e) (f)) was observed. Apparently, no significant organic waste contamination is fed into the lake either by its major tributary, Riviére Kinojevis or by the surrounding cottage population.



Distribution of Fe and Al with Sediment Depth

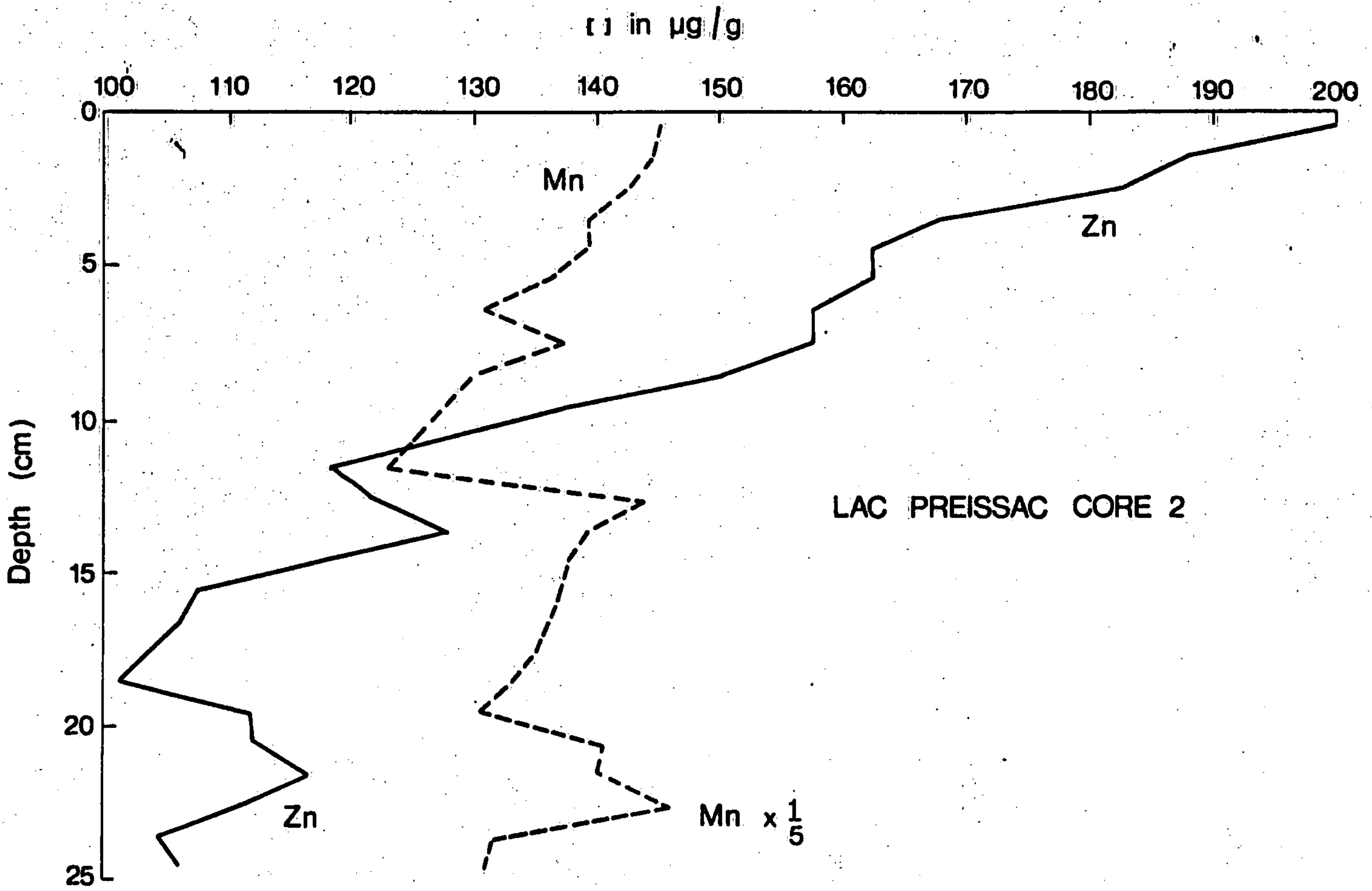


Figure 6(b). Distribution of Zn and Mn with Sediment Depth

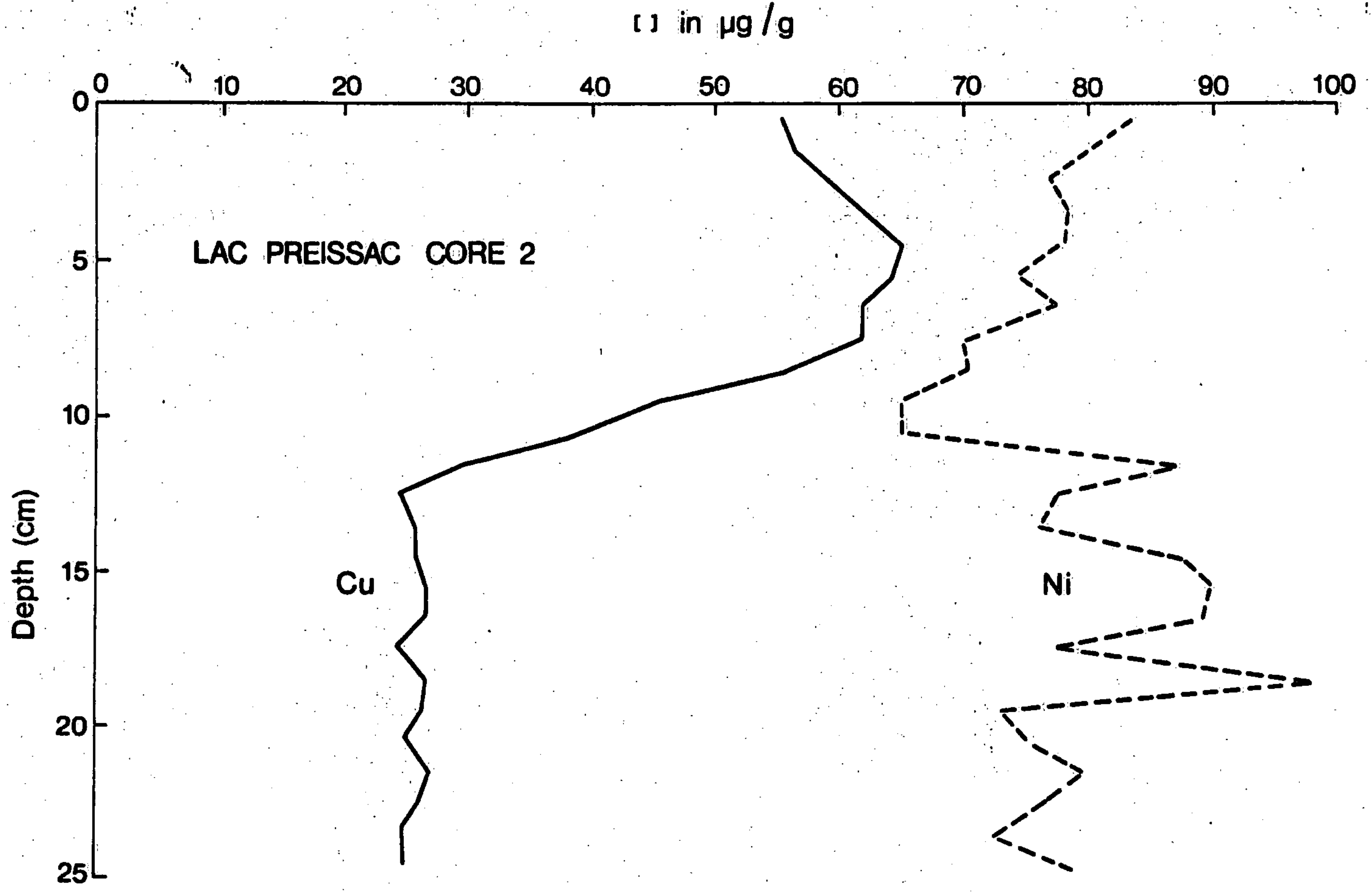


Figure 6(c). Distribution of Cu and Ni with Sediment Depth

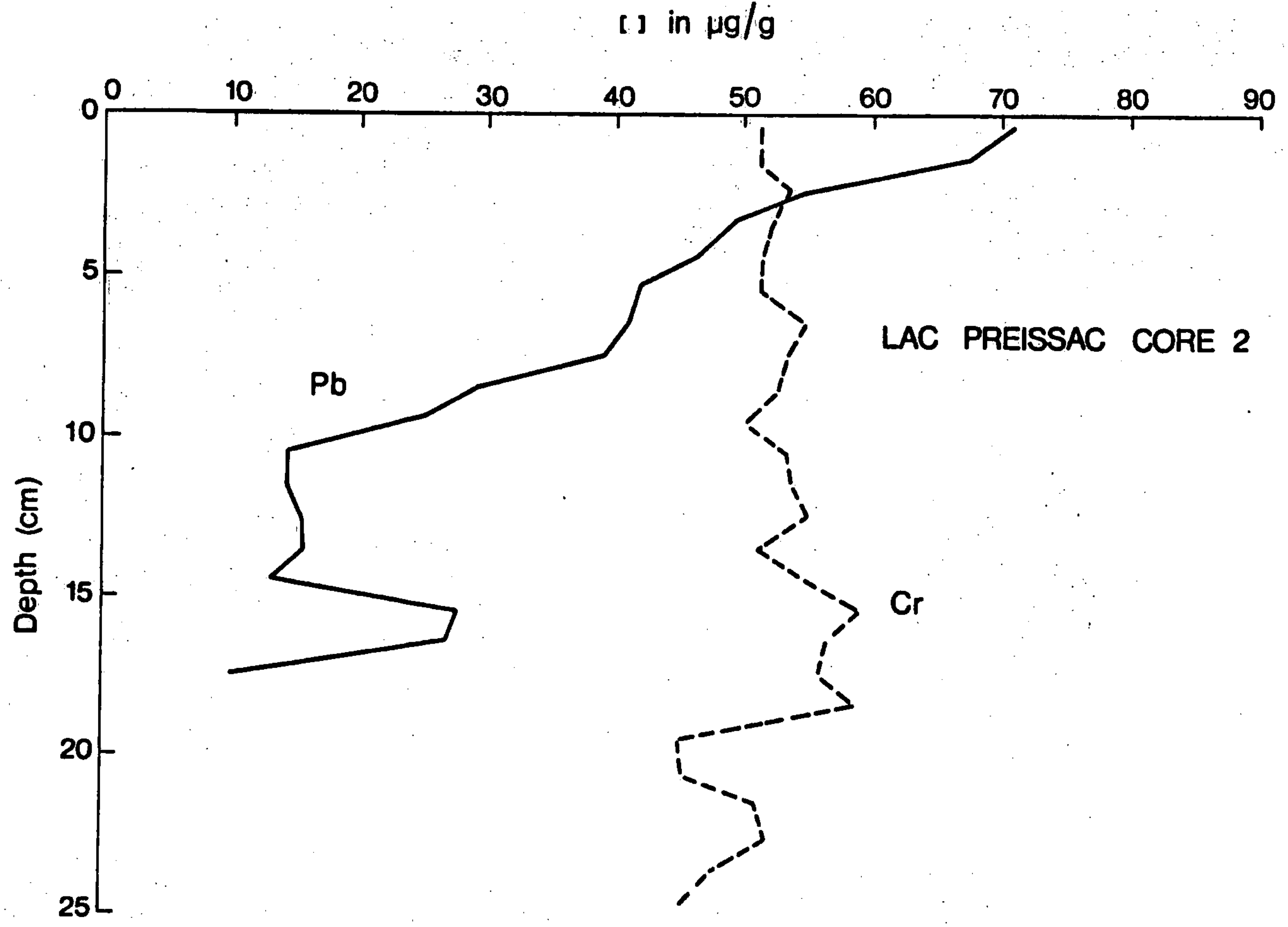
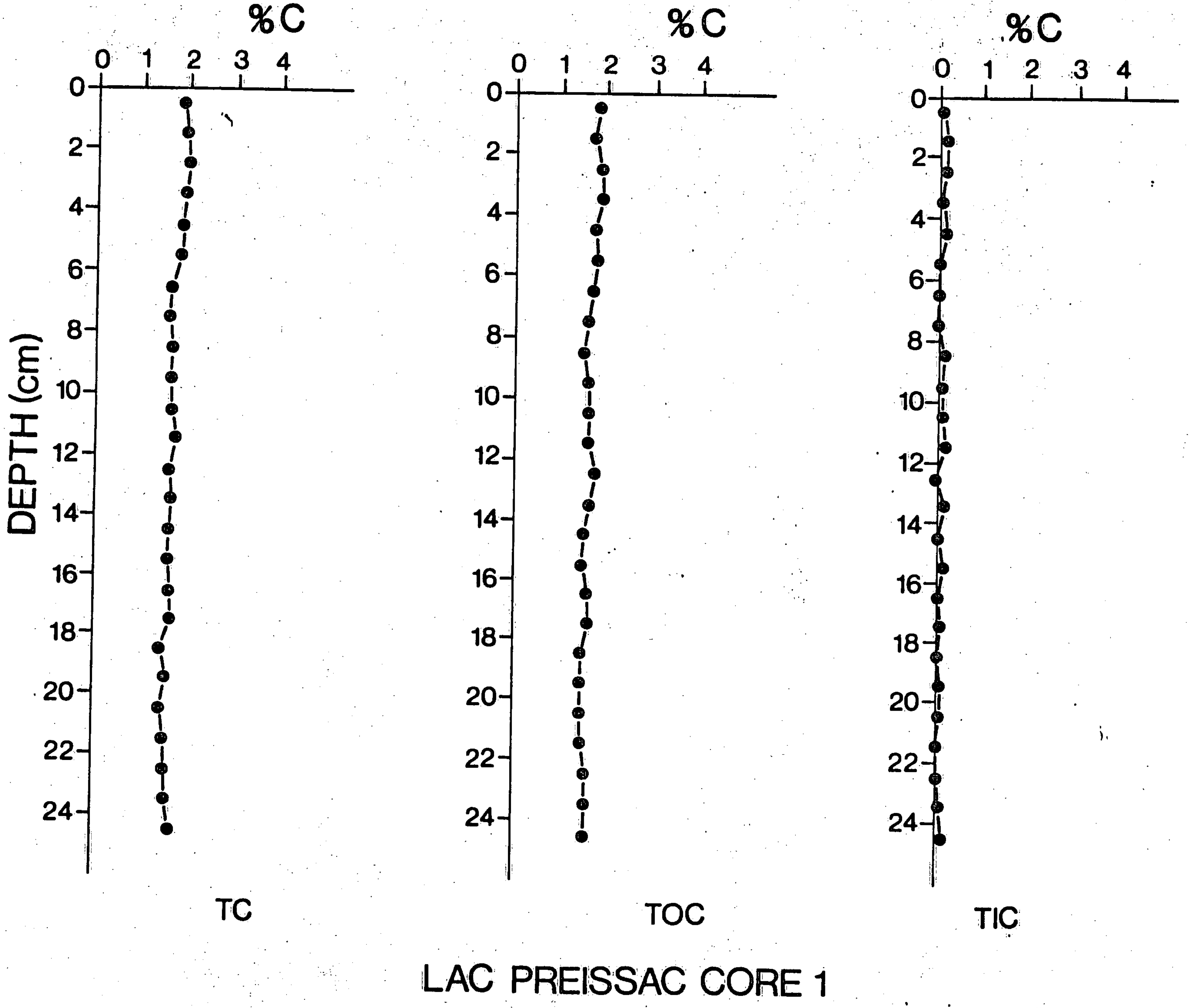


Figure 6(d). Distribution of Cr and Pb with Sediment Depth

Figure 6(e). Total Carbon, Total Organic Carbon, and Total Inorganic Carbon Distributions with Sediment Depth



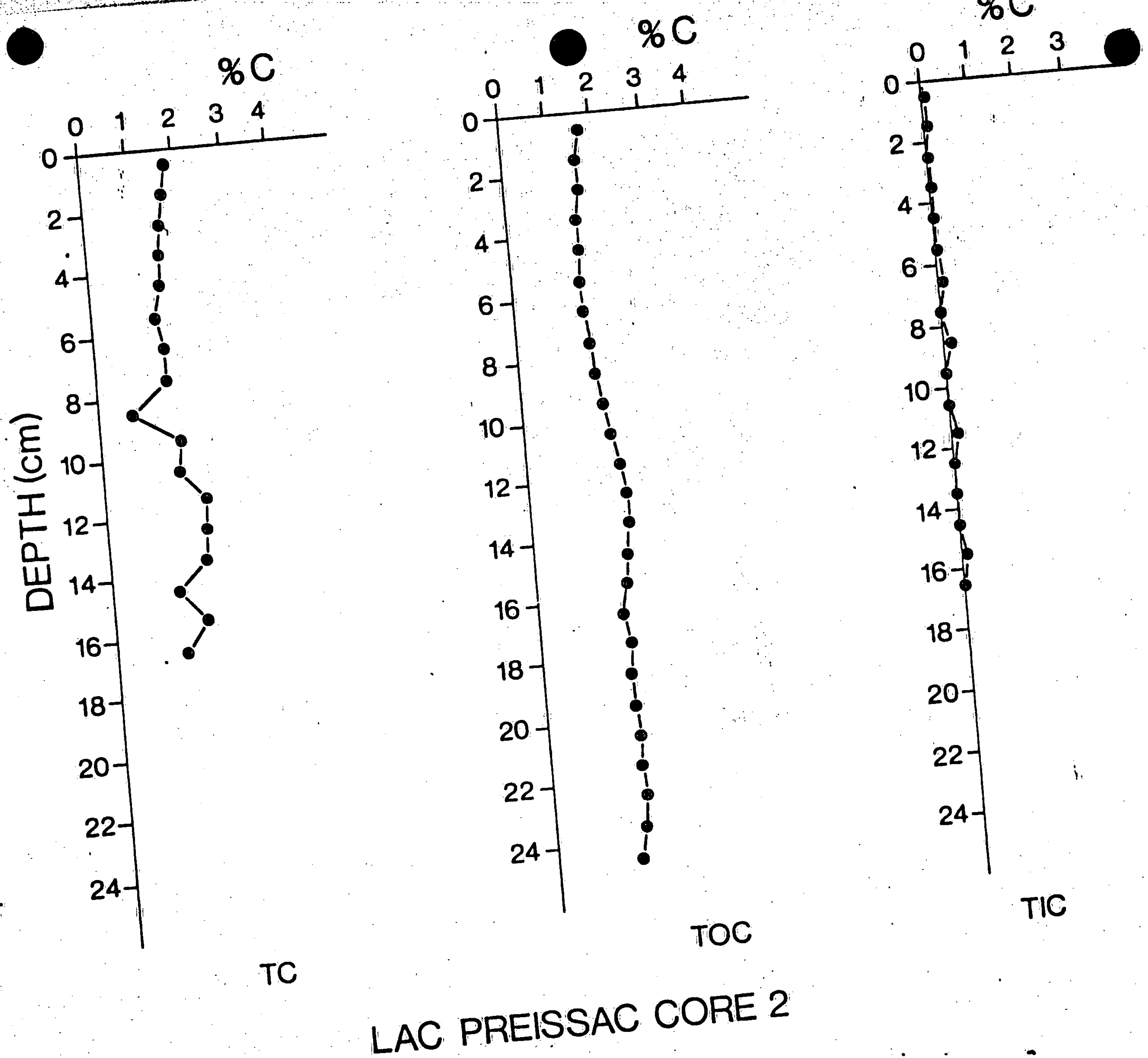


Figure 6(f). Total Carbon, Total Organic Carbon, and Total Inorganic Carbon Distributions with Sediment Depth

Lac Chassignolle

Lac Chassignolle is located approximately 35 km east of the Noranda smelter at approximately 48°20'N, 78°28'E and is connected by a narrow channel at its southeast end to Lac Preissac. The core was obtained from a depth of 8 m with the EBT profile indicating isothermal conditions in the water column. Oxidizing conditions prevailed throughout the core with a surface Eh of +270 mV and pH of 6.4.

The metal profiles as well as metal levels were comparable to those of Lac Preissac. Such behaviour was not altogether unexpected. The same mining operations that Lac Preissac is exposed to are present to the northeast of Lac Chassignolle. Furthermore the fact that the two lakes are connected makes metal transport from Preissac to Chassignolle a distinct possibility (note that in this region, the natural flow of water is south).

In general, the metal enrichment begins in the 5-6 cm section, with increases in the levels of Mn, Zn, Cu and Fe (Figures 7(a), (b), (c)). The behavior of Al (Figure 7(c)) is similar to that of other lakes, where increased levels of surface silt (Figure 7(e)) result in lower Al levels (this was verified by x-ray diffraction and particle size analysis). Both Ni and Cr (Figures 7(b) (d)) levels remained constant while neither Cd nor Mo were detected.

Here, as in Lac Preissac, the carbon levels Figure 7(f) remained relatively unchanged, thereby suggesting no significant organic waste influx from the surrounding area.

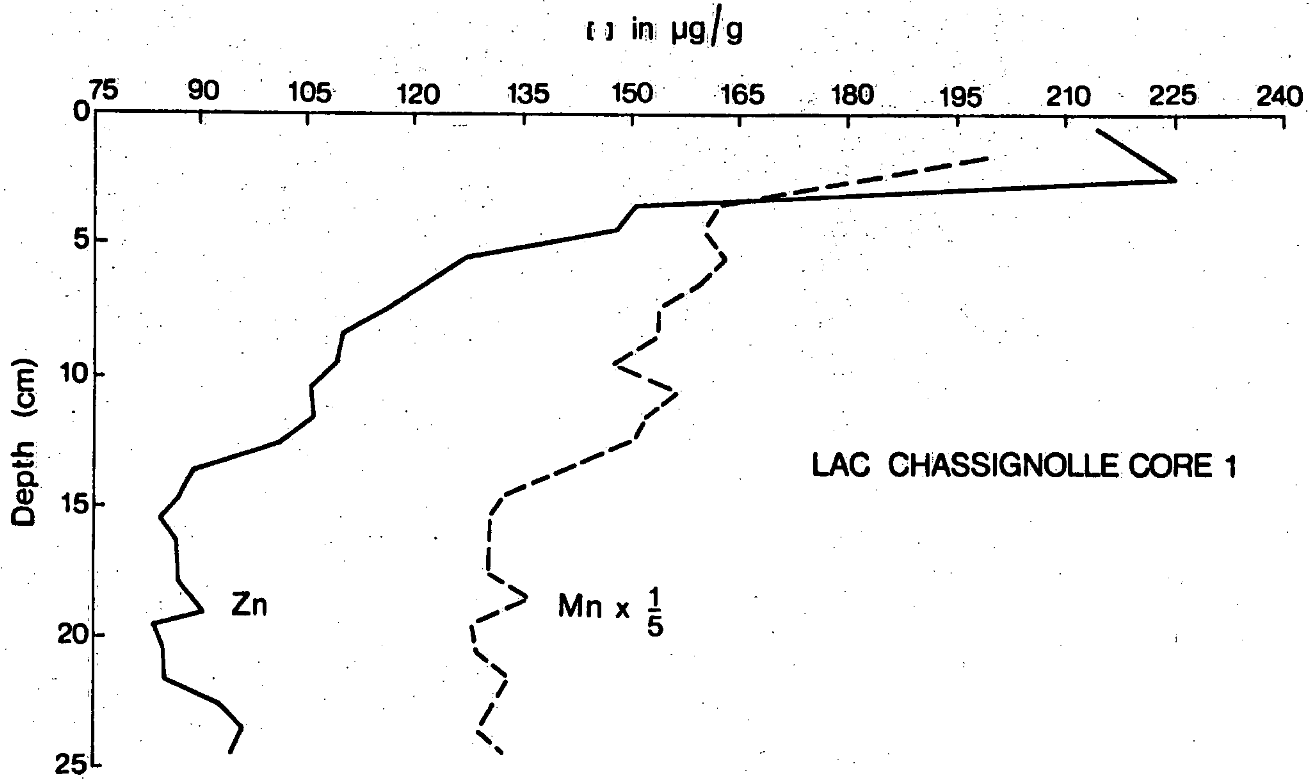


Figure 7(a). Distribution of Mn and Zn with Sediment Depth

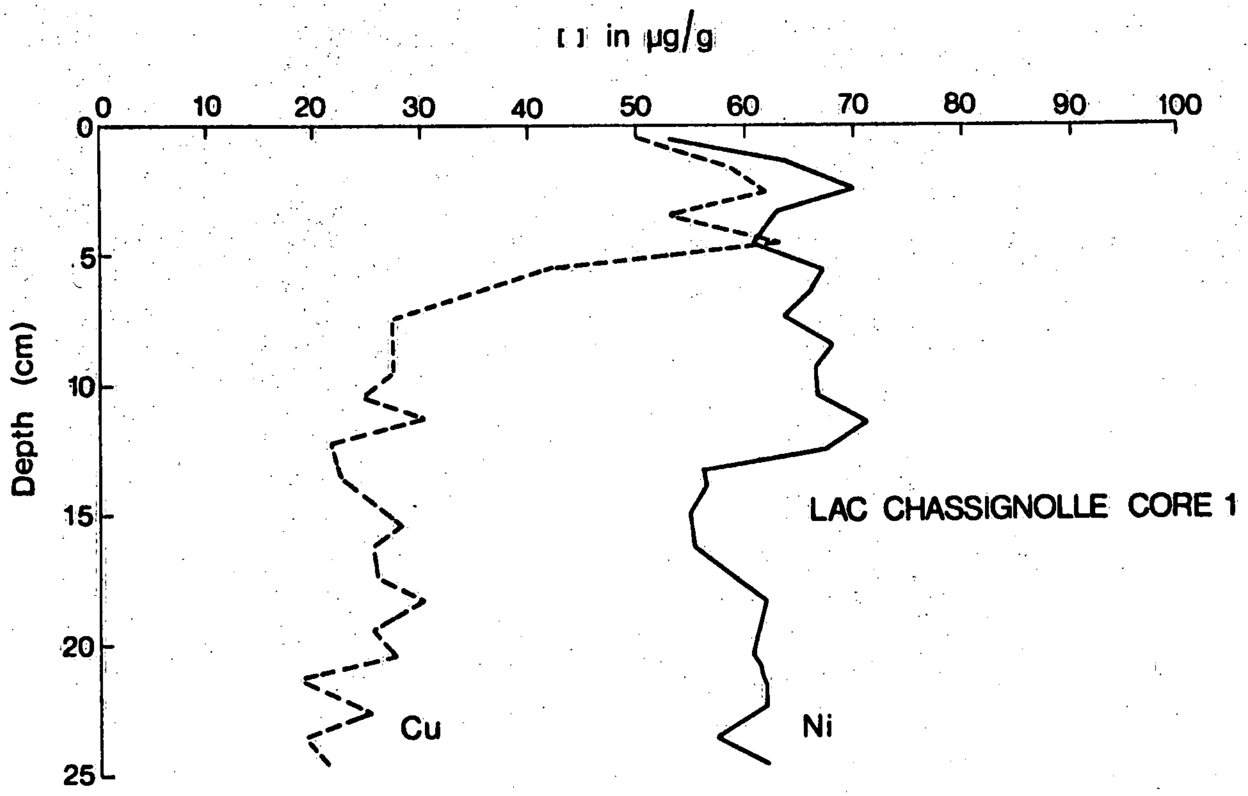


Figure 7(b). Distribution of Cu and Ni with Sediment Depth

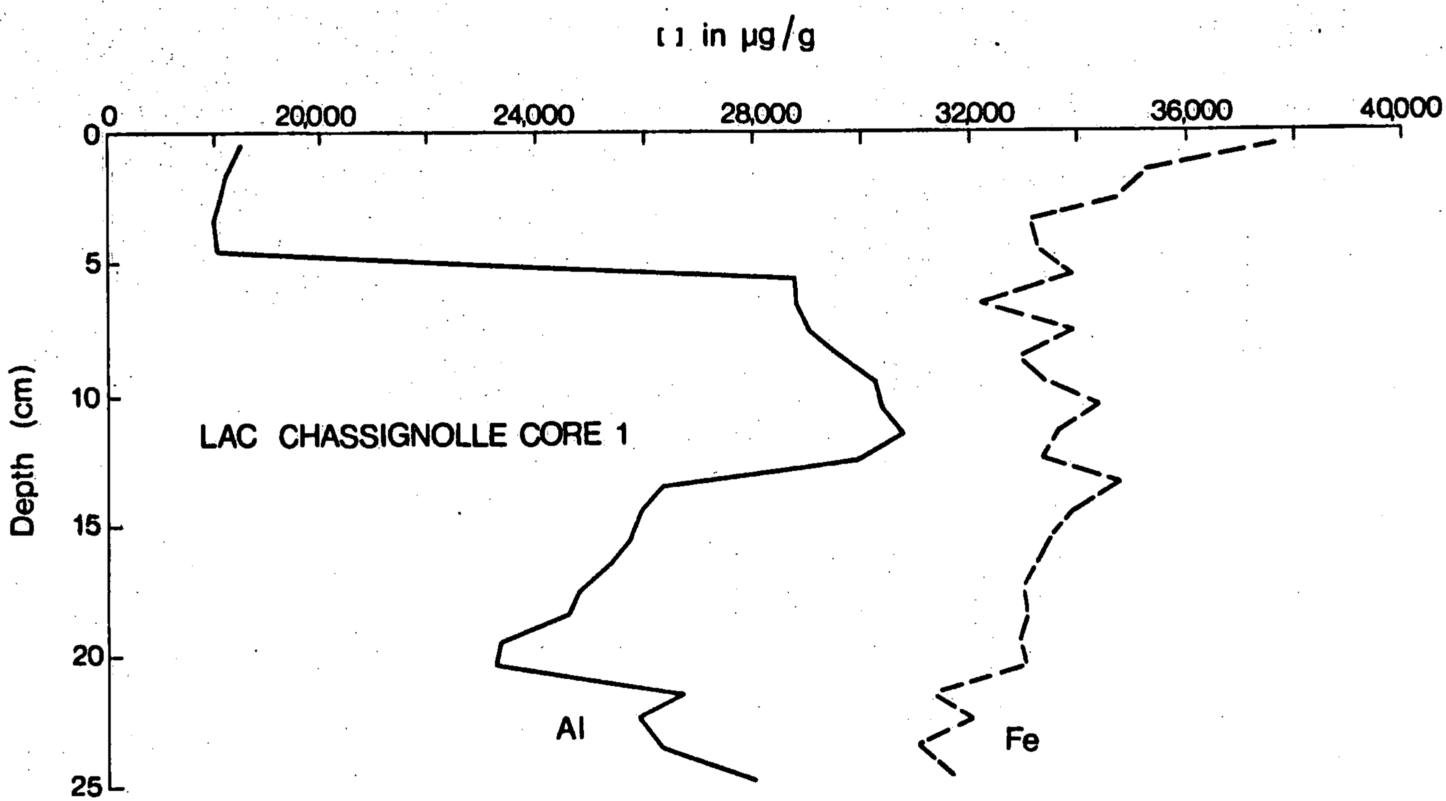


Figure 7(c). Distribution of Fe and Al with Sediment Depth

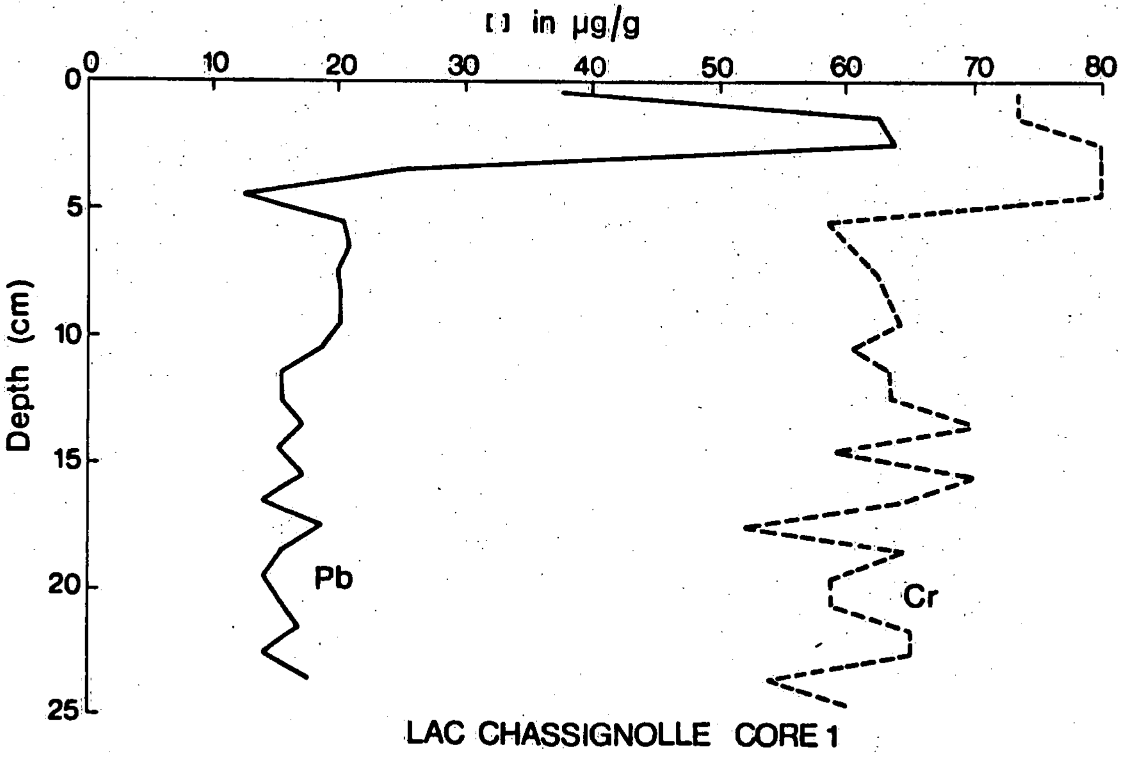


Figure 7(d). Distribution of Cr and Pb with Sediment Depth

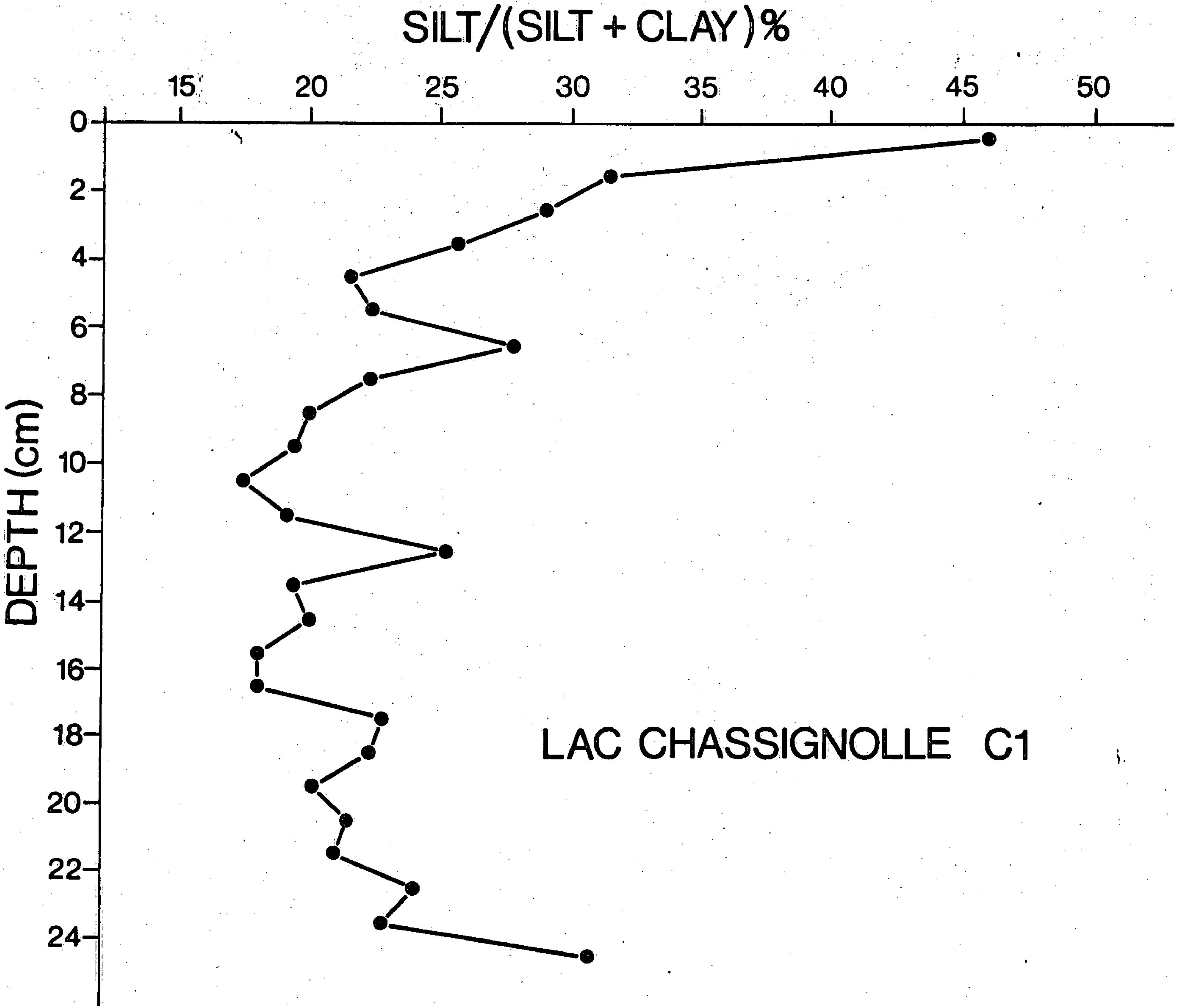


Figure 7(e). Distribution of Silt/(Silt + Clay) with Sediment Depth

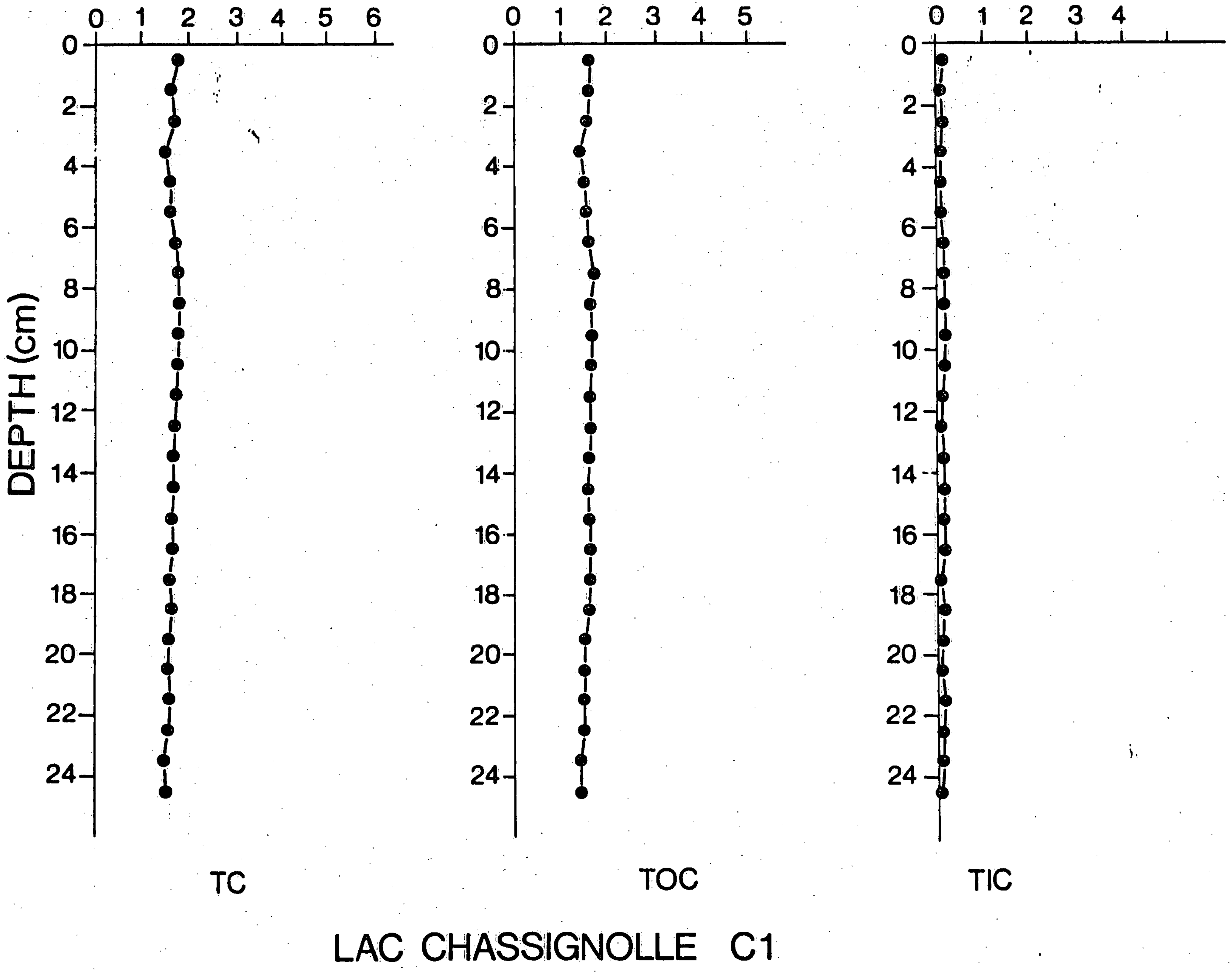


Figure 7(f). Total Carbon, Total Organic Carbon, and Total Inorganic Carbon Distributions with Sediment Depth

Lac Opasatica

Lac Opasatica is located approximately 25 km to the southwest of the smelter at approximately 48°04'N, 79°19'E. The core was obtained from a depth of 15 m with the EBT profile indicating stratified temperature conditions in the water column. Strongly oxidizing conditions were observed throughout the core, with a surface Eh of +560 mV and pH of 7.4.

Unlike most of the other lakes studied (excepting Macamic) which were directly exposed to contaminant sources, Lac Opasatica has neither mines nor tailing ponds on or near its shores. The closest such sources are abandoned mines approximately 9 km to the northeast near Arntfield. However, there is still noticeable metal enrichment at the 4 cm depth with increasing levels of Fe, Mn, Zn, Cu, and Al (Figures 8(a) (b)) nearing the surface. Pb, Mo and Cd were not detected. The elevation in metal levels in the surface layers appears to have occurred via aerial deposition. (An earlier report by Arafat and Glooschenko[2] using moss samples from the same general area suggests the same). However, as in lakes Preissac and Chassignolle, the natural water flow is southerly and metal transport through the water system is a possibility.

The mineralogy in the lake sediments was the same as that for other lakes with the exception that calcite was also present (see

Table 5). A higher level of inorganic carbon (1.6%) was also detected (Figure 8(d)) as compared to 0.1% levels found in the other lakes studied.

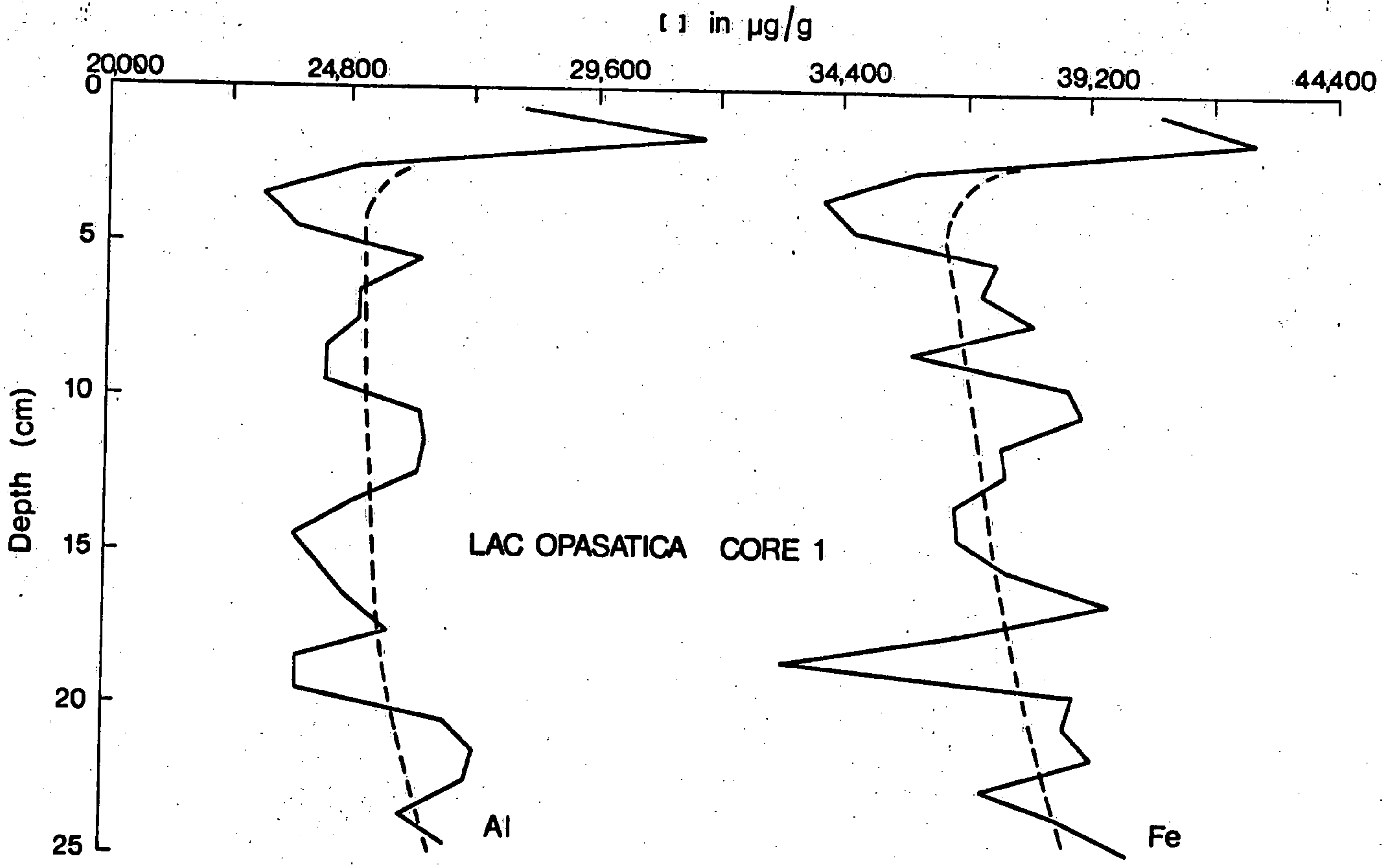


Figure 8(a). Distribution of Fe and Al with Sediment Depth

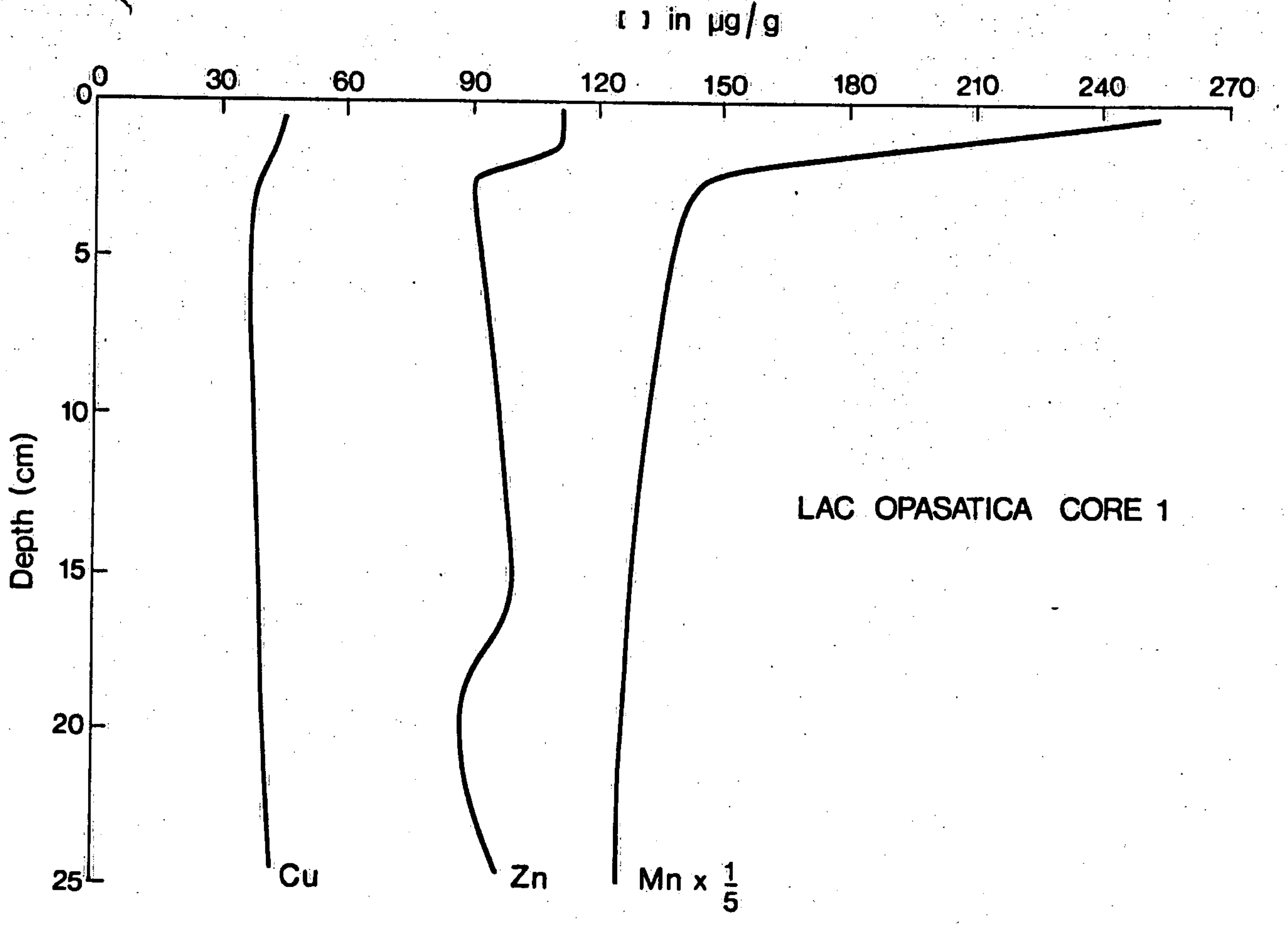


Figure 8(b). Distribution of Cu, Zn, and Mn with Sediment Depth

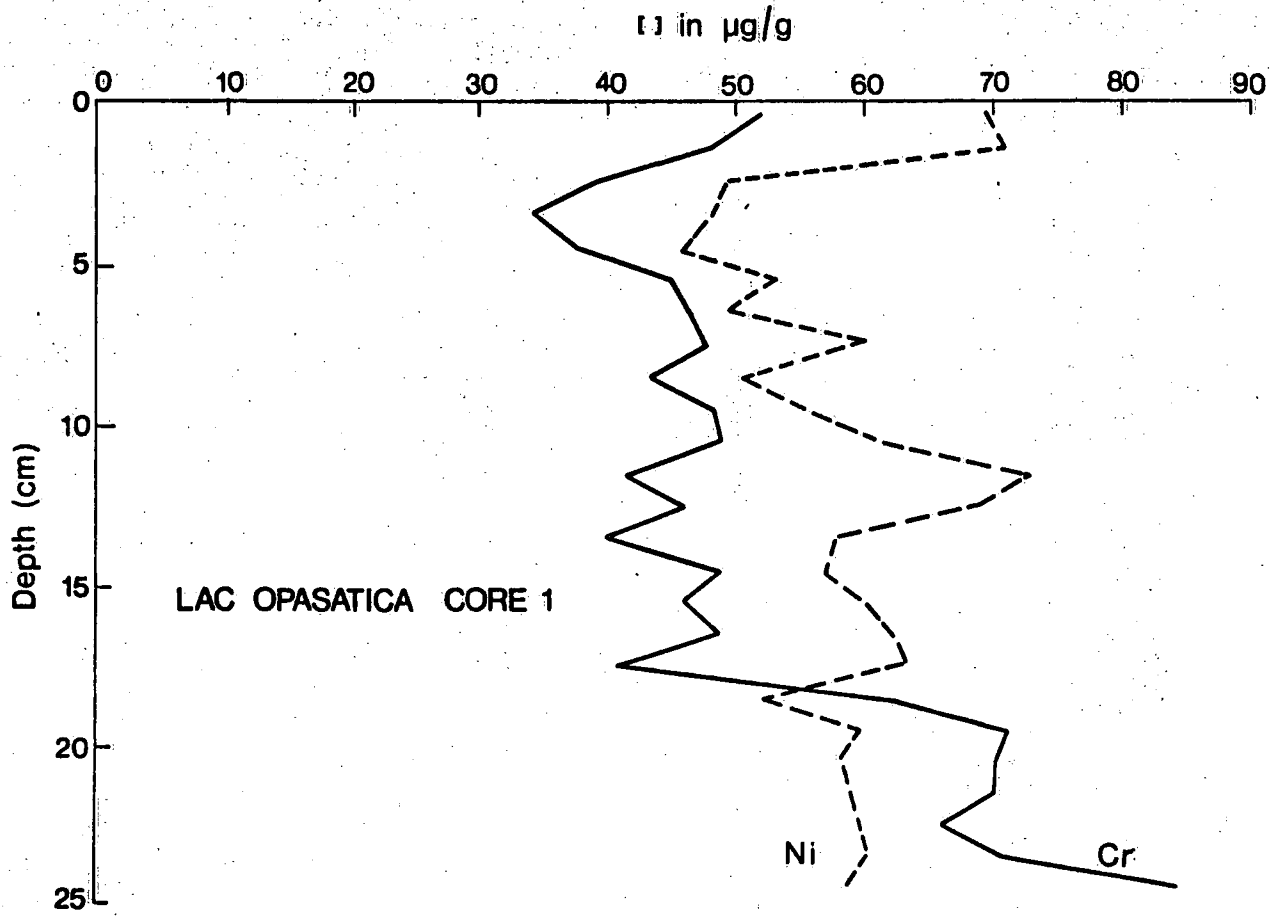


Figure 8(c). Distribution of Ni and Cr with Sediment Depth

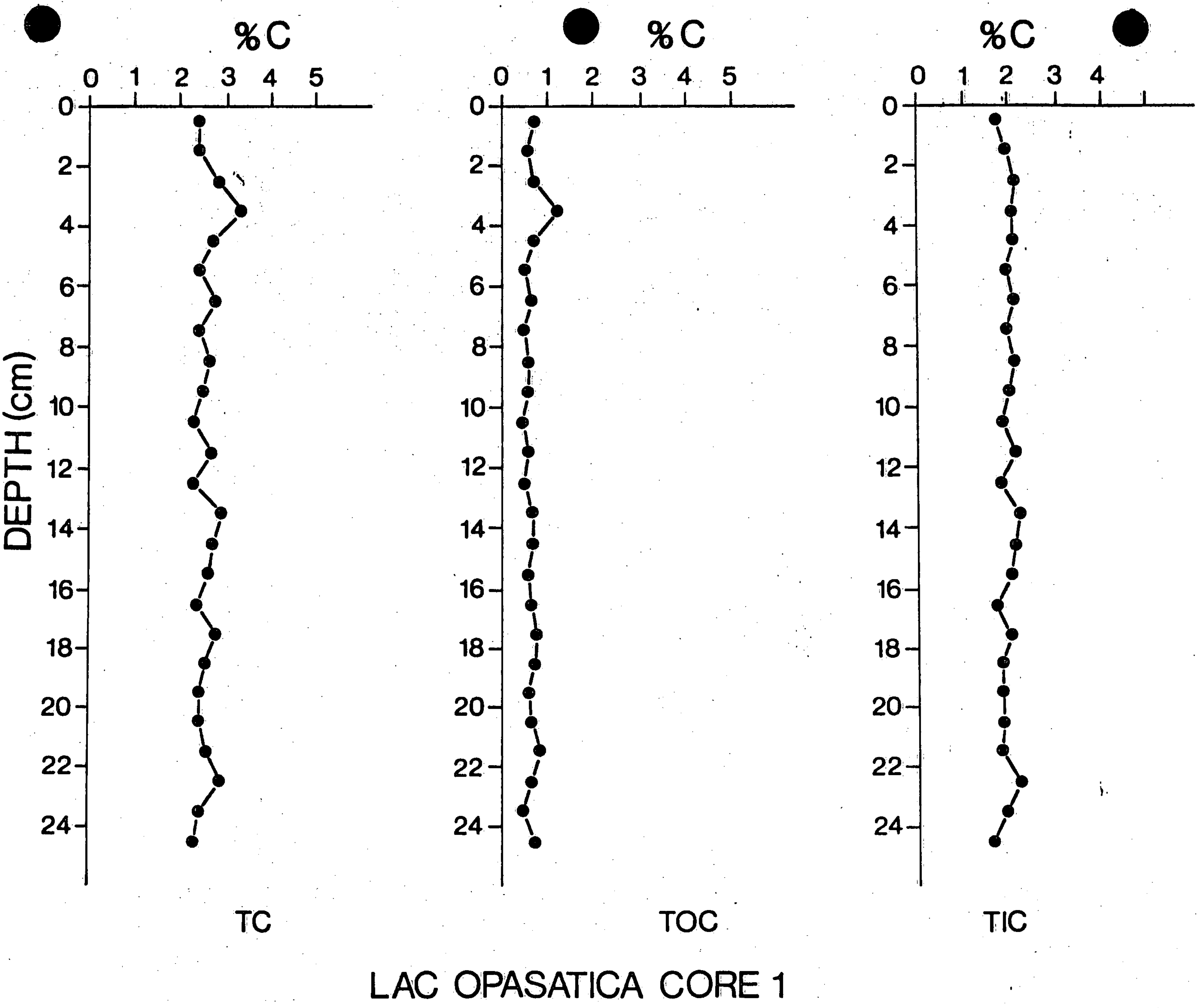


Figure 8(d). Total Carbon, Total Organic Carbon, and Total Inorganic Carbon Distributions with Sediment Depth

The sediment enrichment factors (SEF) (Table 4) were calculated by taking the average metal content in the top 2 cm of sediment and dividing the value by the average background level. Lac Osisko, located in Rouyn-Noranda approximately 1.5 km from the smelter, exhibited high enrichment factors in Cu, Zn and Pb with values of 166, 118 and 130 respectively. Lac Dufault, located approximately 8 km north of the smelter, had SEF values of 145, 25 and 90 for the same metals respectively. The remainder of the lakes (Duparquet, Preissac, Chassignolle, Macamic, and Opasatica), all located 25 km or more from the smelter, had SEF's ranging from 1 to 5.5, the exception being Lac Duparquet where a value of 25 was obtained for Mo. This is probably due to Mo being processed at the former Beattie Gold Mine on the shores of the lake. A comparison of our results with those obtained by Nriagu _et al_. (1982)[8] dealing with Sudbury area lakes, which are similar to the lakes in our study area from a mining/smelting point of view, yields some parallels (the SEF's of the Sudbury study are listed in Table 6). The SEF data from both studies suggests a trend of decreasing metal enrichment with distance travelled from the smelter. Such a trend is further indicated in two additional studies by Arafat and Glooschenko (1981[2] and 1982[9]) dealing with levels of As and Se in both the Sudbury and Rouyn-Noranda regions. It is apparent that the mechanism of atmospheric transport of heavy metals is most effective in the area of the smelter proper (a radius of approximately 15 km or less) as seen in the SEF's for lakes Osisko, Dufault, Ramsey, McFarlane, and Vermillion. As the distance between the smelter and the sampling station increased, a significant drop in metal enrichment occurred (lakes Duparquet, Macamic, Preissac, Chassignolle, Opasatica, and Windy). A marked difference in the absolute values of the SEF's existed between the Sudbury and Rouyn-Noranda area lakes. The reason lies in the fact that the Sudbury lakes rely almost exclusively on atmospheric transport as the method by which the heavy metals are distributed. There are no mine-tailing ponds or similar contamination sources near these Sudbury lakes. In Rouyn-Noranda, however, apart from aerial deposition, contaminant sources such as abandoned mines, mine-tailing ponds, and active metal processing plants are located near the lakes. Minor variations in SEF's may also be caused by the differences in the composition of the ores smelted (in Sudbury, Ni is the metal of interest while in Rouyn-Noranda, it is Cu), resulting in different by-products, as well as differences in the technology used in plant operations. Because of such factors, these numerical differences are not altogether unexpected.

In terms of absolute levels of the studied metals, lakes Osisko and Dufault had the highest concentrations. Their contamination was, and still is, a result of the mining/smelting operations, aerial deposition, land runoff, as well as waste discharges. Further away from the smelter (in lakes Duparquet, Preissac and Chassignolle), the major contamination source was not the smelter but local pollutors (see each individual lake section). Lac Macamic, furthest from the smelter at 60 km, was found to have relatively constant levels of metals throughout the core. Thus, the effect of atmospheric transport of heavy metals to outlying lakes appears to be minimal. A comparison of our sediment metal concentrations with those obtained in a study on Lake Erie by Walters et al. (1974)[10] clearly shows how the surrounding industries affect the type of pollution entering the lakes. (The surface sediment metal concentrations for both the Rouyn-Noranda lakes and Lake Erie are found in Table 7). While industrialization in the Rouyn-Noranda area is primary and secondary in nature (e.g. mining and smelting), secondary and tertiary industries (processing and support services) predominate around Lake Erie. As such, different contamination sources exist. Whereas in Rouyn-Noranda the smelter and mine-tailing ponds are of primary concern, the waste discharges of the manufacturing industries surrounding Lake Erie are of considerable importance. Most of the contamination of Lake Erie appears to be organic in nature, whether it be chemical dumping or nutrient influx. To this end, significantly higher levels of organic carbon was found by Kemp in a 1969 study[11]. From the results quoted in Table 7, it is clear that even with mineralogical differences between the Lake Erie and Rouyn-Noranda regions, the major deciding factor in heavy metal levels is the type of industry in the region. Thus, the numbers from Rouyn-Noranda are significantly higher.

In lakes Osisko and Dufault, the highest sulphate levels in the surface waters were found (Table 3), probably due to the heavy SO_2 emissions from the Noranda stacks. Similarly, Ca^{2+}, Mg^{2+} and Na^+

levels are slightly elevated when compared with other regional lakes. The elevation in Ca^{2+} may be attributed to the ~~lining~~ liming of mine-tailing ponds in the area, with subsequent lake water contamination through spring runoff or streams. Similar results were obtained in a study by Azzaria and Potvin (1979)[12].

Although at the present time, water pH's are near the neutral point and there is no immediate danger of metals leaching into the water, concern should be expressed regarding Lac Dufault, for it is from this lake that Rouyn-Noranda draws its municipal drinking water. The high levels of heavy metals in its surface sediments are a potential for fluxing or leaching into the water if a significant pH drop occurs. While acidification occurs primarily via the SO_2 route, another source is that of seepage of mine tailings into the lakes. The by-product of sulfide ore smelting usually contains pyrite (FeS_2) and under oxidizing conditions (which predominate in this region), sulphuric acid can form[13]:

$$2FeS_2 + 15/2\ O_2 + 4H_2O \rightarrow Fe_2O_3 + 8H^+ + 4SO_4^{=}$$

Thus, care should be taken not only to minimize the future SO_2 outputs from the smelter, but also to prevent existing mine-tailings from entering the lakes.

Lac

A secondary, though important, concern is that involving ~~lac~~ Duparquet. The water flow in this region is naturally northerly. Contaminants, then, may be transported from Lac Duparquet into Lake Abitibi through Rivière Duparquet and thus from Quebec to Ontario.

As mentioned at the beginning of the report, this study was a general overview of the transport of heavy metals in the Rouyn-Noranda region. As such, more specific interpretations than those already offered here can not be made simply because of the lack of detailed investigation. However, with this study, the basis for follow-up projects has been established.

REFERENCES

1. Chartrand, L., Noranda Ordered to Clean Up, Probe Post, October, 1982.

2. Arafat, N.M. and Glooschenko, W.A., Arsenic and Selenium in Bog Vegetation as Indicators of Atmospheric Pollution from Ore Smelters in North-West Quebec, N.W.R.I. Unpublished Report, 1981.

3. Groupe "Ecologie", Etude des sédiments de la région de Rouyn-Noranda: Bureau d'étude sur les substances toxiques, services de protection de l'environnement du Québec, rapport sectoriels E-1 a E-17, 1979.

4. Duncan, G.A., Particle Size Data Report for Rouyn-Noranda Lakes, N.W.R.I. Unpublished Report, 1982.

5. Harper, N.S., Palynology of a Lac Chassignolle Core, N.W.R.I. Unpublished Report, 1983.

6. Gorham, E. and Swaine, D.J., The Influence of Oxidizing and Reducing Conditions upon the Distribution of Some Elements in Lake Sediments, Limnol. Oceanogr. 10:268-279 (1965).

7. Sloterdijk, H. et Azzaria, L.M., Etude des sédiments de la région de Rouyn-Noranda: Bureau d'étude sur les substances toxiques, services de protection de l'environnement du Québec, rapport sectoriel E-8, 1979.

8. Nriagu, J.O., Wong, H.K.T. and Coker, R.D., Deposition and Chemistry of Pollutant Metals in Lakes around the Smelters at Sudbury, Ontario, Environ. Sci. Technol., Vol. 16, No. 9, 551-560, 1982.

9. Arafat, N.M. and Glooschenko, W.A., The Use of Bog Vegetation as an Indicator of Atmospheric Deposition of Arsenic in Northern Ontario, Environmental Pollution (Series B) 4 (1982) 85-90.

10. Walters, L.J., Wolery, T.J. and Myser, R.D. Occurrence of As, Cd, Co, Cr, Cu, Fe, Hg, Ni, Sb, and Zn in Lake Erie sediments, Proc. 17th Conf. Great Lakes Res. 1974: 219-234.

11. Kemp, A.L.W., Organic Matter in the Sediments of Lakes Ontario and Erie, Proc. 12th Conf. Great Lakes Res. 1969: 237-249.

12. Azzaria, L.M. et Potvin, C., Qualités physico-chimiques de l'eau de Rouyn-Noranda, les cahiers de centreau, Vol. 3, No. 1: Centre de recherches sur l'eau, Université Laval, 1979.

13. Bolt, G.H. and Bruggenwert, M.G.M., Soil Chemistry, A., Basic Elements, Elsevier Scientific Publishing Company, Amsterdam, 1978, p. 281.

Table 1: Sediment Extraction Results of Triplicate Runs

	Standard Deviation	Coefficient of Variation (%)
Al	318.0	1.6
Cr	2.2	3.5
Cu	0.4	2.3
Fe	869.6	1.6
Mn	6.7	1.1
Ni	1.9	4.3
Zn	1.3	1.5

able 2. Physical Properties

Lake	Water pH	Surface Water Temp (°C)	Sediment Temp (°C)	Sediment Eh (mV) 0-1 cm	Sediment Eh (mV) 6-7 cm	Sediment pH 0-1 cm	Sediment pH 6-7 cm	EBT Profile
Osisko	6.9	16.6	14.6	-110	+160	6.6	-	8.0 m depth isothermal
Dufault C1	6.5	17.9	14.5	+150	+ 80	7.2	6.8	8.0 m depth isothermal
C2	6.9	17.1	4.0	+160	+ 20	6.9	6.9	15.0 m depth stratified
Duparquet	-	16.6	-	+370	+225	6.6	7.7	7.0 m depth rough and turbulent conditions slightly stratified
Macamic	6.4	14.7	-	+315	+310	6.4	6.4	2.0 m depth isothermal
Preissac C1	6.7	16.3	14.5	+340	+340	6.6	6.6	12.0 m depth isothermal
C2	6.8	16.0	13.7	+460	+410	6.9	6.5	16.0 m depth slightly stratified
Chassignolle	-	16.8	15.8	+270	+400	6.4	6.5	8.0 m depth isothermal
Opasatica	6.6	16.2	10.7	+560	+370	7.4	7.8	15.0 m depth stratified

→ Surface water pH

Table 3. Surface Water Analysis (unfiltered samples)

	Total Trace Element in Surface Waters µg/L							Major Ion in Surface Waters µg/L								
Lake	Cu	Ni	Mn	Al	Fe	As	Se	Ca	Mg	Na	K	SO_4	Cl	SiO_2	Alk
Osisko	17	4	100	15	220	1.2	0.2	28.1	7.3	14.6	2.3	81	18.5	3.5	18.8
Dufault	18	L.1	65	26	120	–	–	23.1	4.3	4.8	1.0	56	2.5	1.3	15.3
Duparquet	6	L.1	L.20	300	610	–	–	–	–	–	–	–	–	–	–
Macamic*	5	L.1	20	1100	1500	–	–	10.5	3.1	1.9	1.3	9.1	1.7	2.9	27.5
Preissac	5	L.1	20	320	520	–	–	6.2	1.7	1.6	0.77	8.4	1.2	3.6	11.0
Chassignolle	5	L.1	L.20	420	610	–	–	6.1	1.8	1.4	0.80	7.4	1.0	3.0	–
Opasatica	5	L.1	20	140	190	–	–	9.4	3.7	2.7	1.1	12.6	2.4	1.5	25.7

L. less than
* light brown water

Table 4. Enrichment Factors in Sediment Cores

$$\text{where FACTOR} = \frac{\text{AVERAGE ENRICHMENT IN TOP 2 cm, } \mu g/g}{\text{AVERAGE BACKGROUND (PRECOLONIAL) LEVEL, } \mu g/g}$$

Lake	Fe	Cu	Mn	Zn	Al	Cr	Ni	Mo	Pb	Cd
Osisko	6	166	L.1	118	L.1	1	2	-	130	13.2
Dufault C2	6	145	1	25	1	L.1	1.5	-	90	4
Duparquet C2	1	5	1	2	L.1	1	L.1	25	3	-
Macamic	1	1	1.5	1	L.1	1	L.1	-	-	-
Preissac C2	1	2	1.5	2	L.1	1	1	-	5.5	-
Chassignolle	1	2	1.5	2.5	L.1	1	L.1	-	3.5	-
Opasatica	1	1	1.5	1	1	L.1	1	-	-	-

L. less than

Table 5. X-ray Diffraction Data

Lake	Sample Depth (cm)	Composition
Osisko	0- 1 4- 5 14-15	No difference in minerals between the 0-1 cm and 14-15 cm sections. QUARTZ, PLAGIOCLASES, AMPHIBOLES, MUSCOVITE, CHLORITE, and ILLITE. However, mineral levels in top section lower than in lower section.
Dufault C2	2- 3 22-23	Same minerals as above. Mineral levels in lower section higher than in top section
Macamic	0- 1 2- 3 5- 7 13-14 20-21	Same minerals as above. Consistent levels throughout.
Preissac C2	0- 1 5- 6 12-13 19-20	Same minerals as above. Consistent levels throughout.
Chassignolle	11-12	As above.
Opasatica	12-13	Same minerals as the other lakes except that CALCITE also observed.

Table 6. Sediment Enrichment Factors for Sudbury Area Lakes

Lake	Distance from Smelter (km)	Metal			
		Ni	Cu	Pb	Zn
Ramsey	4.5	38	36	5.9	2.6
McFarlane	6.0	18	31	3.2	1.8
Vermilion	16	12	10	2.2	1.7
Windy	20	2.5	1.1	3.8	1.0

Table 7. Heavy Metal Levels in the Surface Sediments from Lake Erie and the Rouyn-Noranda Area Lakes

	Metal Concentration (μg/g)					
Lake	Fe	Cr	Cd	Zn	Ni	Cu
Osisko	221,875	63	132	14,469	103	7,297
Dufault	235,500	26	35	3,300	85	3,480
Duparquet	46,750	62	N.D.	222	49	84
Opasatica	40,437	52	N.D.	111	69	45
Preissac	38,625	51	N.D.	200	84	55
Chassignolle	37,625	74	N.D.	214	52	50
Macamic	3,625	59	N.D.	88	36	22
Erie 34-2	11,000	12	N.D.	53	32	12
16-1	28,000	60	3.8	26	56	40
13-2	23,000	37	1.0	18	65	31

N.D. not detected

34-2 Buffalo Harbour
16-1 Cleveland Harbour
13-2 South of Detroit