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SEDIMENT PHOSPHORUS RELEASE REDUCED THE EFFECT OF THE CHAIN LAKE WATER DIVERSION

By

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Réduction de l'effet de la dérivation des eaux du lac Chain par le rejet de phosphore sédimentaire

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RÉSUMÉ

En 1968, un canal de dérivation de 2 km de longueur a été aménagé afin d'alimenter le lac Chain (Colombie-Britannique) en eau subalpine pauvre en éléments nutritifs. Malheureusement, en quelques années les algues bleu-vert se sont multipliées (chl a >100 µg/L) et les poissons meurent toujours. Ce succès partiel est dû à l'asynchronie de l'écoulement de l'eau et du rejet de phosphore par les sédiments. La charge interne représente environ 78 % de l'apport en phosphore en été, et l'écoulement de l'eau est négligeable au moment du rejet de phosphore. La teneur en phosphore des sédiments superficiels est cinq fois supérieure à celle des sédiments prélevés à plus de 80 cm de profondeur. La présence de diatomées dans les carottes de sédiments indique que le lac a été eutrophe pendant au moins 300 ans. L'accumulation de boues à diatomées, mesurée par trois méthodes, varie de 0.5 à 1 cm par année. La construction d'un canal de dérivation plus large résoudrait le problème de la multiplication des algues, mais favoriserait la croissance de macrophytes; le dragage des sédiments pourrait être un traitement *in situ* plus efficace.

Réduction de l'effet de la dérivation des eaux du lac Chain par le rejet de phosphore sédimentaire

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PERSPECTIVES DE GESTION

L'apport et l'import d'éléments nutritifs dans le lac Chain, en Colombie-Britannique, ont fait l'objet d'une surveillance en vue de déterminer pourquoi la dérivation des eaux de la rivière Shinish n'a pas permis de réduire l'eutrophisation du lac. Le rejet de sédiments durant les périodes d'étiage n'a pas été modifié sensiblement par l'effet de lessivage des eaux de dérivation. Les études des sédiments ont révélé que le phosphore superficiel est facilement dissous avec l'épuisement de l'oxygène, que la teneur en phosphore des sédiments de surface est cinq fois supérieure à celle des sédiments prélevés à plus de 80 cm de profondeur, que le lac a été eutrophe pendant au moins 300 ans et que les boues à diatomées s'accumulent à raison de 0,5 à 1 cm par année. En dépit du fait que la construction d'un canal de dérivation plus large pourrait réduire l'eutrophisation, un autre traitement, comme le dragage des sédiments, pourrait être appliqué. Les eaux de dérivation pourraient être utilisées plus judicieusement si un bassin était dragué à proximité de l'émissaire pour permettre l'utilisation d'un syphon hypolimnétique afin de faciliter l'élimination du phosphore.

Sediment Phosphorus Release Reduces the Effect of the Chain Lake Water Diversion

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In 1968, a 2 km long water diversion was built to flush Chain Lake, British Columbia with nutrient-poor subalpine water. Unfortunately in some years, blue-green algal blooms (chl a >100 µg/L) and fish kills still occur. The incomplete success of the diversion is related to the asynchrony of water flow and phosphorus release from the sediments. Internal loading represents about 78% of the phosphorus supply to the lake in summer, and water flow is minimal during phosphorus release. Phosphorus is five times more concentrated in the surface sediments relative to sediments deeper than 80 cm. Diatoms in sediment cores indicate that the lake has been eutrophic for at least 300 years. The accumulation of a diatomaceous ooze in the lake was measured by three methods to be between 0.5 and 1 cm a year. A larger diversion would suppress plankton blooms, but in this shallow lake it would enhance the growth of macrophytes; sediment dredging may be a more effective *in situ* treatment.

INTRODUCTION

Chain Lake is situated 45 km N.E. of Princeton, British Columbia (longitude 1200°16', latitude 490°42'; Fig. 1). Although it receives a mean rainfall of 52.7 cm a year (Envir. Can., 26 years of data), rainfall is variable and severe water shortages have occurred. To provide more water storage for irrigation of downstream farms, the lake level was raised an unknown amount about 1915, and by 1.2 m in 1957 by the construction of dams on the outlet.

The surface of Chain Lake is approximately rectangular, 1.6 km long and 0.3 km wide. The lake is small (43.7 ha) and relatively shallow (6.1 mean and 7.9 m maximum depth, WIB 1977). The natural inlet, Hayes Creek, is at the north end. The outlet flows from the southern end of the lake to the Similkameen River, which flows into the Okanagan and Columbia Rivers.

Chain Lake lies at an elevation of 1006.5 m upon a Jurassic volcanic intrusion that is rich in the phosphate mineral apatite (Cockfield 1947, Rice 1946). The Chain Lake watershed is heavily forested with Lodgepole pine, Douglas fir, and Trembling aspen at lower elevations, and with Engleman spruce and subalpine fir at higher elevations. Only a few small hobby farms were observed in the watershed. The upstream lakes, Osprey and Link, have less than a hundred cottages and Chain Lake has thirty cottages, two permanent dwellings, and a provincial campground with about twenty campsites.

Algal blooms occur every summer and fish kills have occurred both during summer and winter. A water diversion from Shinish Creek to Chain Lake was constructed in 1968 to reduce eutrophication of the lake. In 1968, little appreciation of sediment phosphorus release existed, and this component of the phosphorus loading model was not used to calculate the required diversion flow. Moreover, some biologists predicted that the diversion would flush the lake too effectively and suppress fish growth (WIB 1977).

Water Investigations Branch (WIB 1977) estimated that in 1971 the diversion supplied 22% of the total outflow of Chain Lake and that Chain Lake had a flushing time of 2.8 months. Ennis (1972) found no significant reduction of eutrophication by the flushing. WIB confirmed this, but they believed that the diversion had not been operating long enough for the effect to be observed.

This study focused on the inability of the Shinish Water Diversion to prevent blue-green algal blooms. The hypothesis that sediment phosphorus release greatly exceeded the rate of phosphorus flushing was developed. A sediment study indicated methods that could utilize the diversion in a dredging program to maintain water levels, produce better fish habitat, and perhaps reduce eutrophication.

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2 METHODS

2.1. Hydrology

Water flow was measured with a Pygmy flow meter that was calibrated at the National Water Research Institute (NWRI). The natural inlet flow was measured in a culvert, the diversion flow was measured at three sites in a rectangular box that was built into the flume, and the outlet flow was measured at nine sites across the concrete spillway of the dam. Flow measurements were made on ten days in 1983. An echo sounder was used to measure water depth (30 transects) and the water height was monitored with an automatic recorder by the British Columbia Water Investigations Branch. Rainfall and temperature were recorded by Environment Canada.

2.2 Water Analysis

Chain Lake water samples were collected in 1983 and 1984 with a three litre PVC Van Dorn water sampler. One station in the middle of the lake between the provincial campground and the diversion was sampled 65 times in 1983 and 1984. Other sites were analyzed less frequently. In 1983, sampling began at the end of the spring runoff; in both years, samples were collected before, during and after the summer algal blooms. Samples were filtered and preserved at the lake within two hours of collection.

Samples for chlorophyll a analysis were filtered through GF/C filters at the lake. The filters were frozen and later analyzed by DMSO extractions (Burnison 1980). Soluble reactive phosphorus was measured the same day as samples were collected with the molybdate-ascorbic acid method (Strickland and Parsons 1972). Samples for total phosphorus were preserved with 0.2 mL of H_2SO_4 per 100 mL sample and analyzed by perchloric acid digestion and the molybdate-ascorbic acid method. Samples for total iron analysis were preserved with 2.0 mL of H_2SO_4 per litre and analyzed at NWRI with a modification of the bathophenanthroline method (Strickland and Parsons 1972).

Samples for dissolved organic carbon, dissolved organic nitrogen, sulphate, chloride, nitrate, potassium, sodium, calcium and magnesium analysis were prepared in the field laboratory and shipped on ice to a laboratory for analysis (Environment Canada 1979). Some ammonia analysis was done at the lake with the Solorzano (1969) method.

2.3 Sediment analysis

Sediment samples were collected with a Williams light weight corer (Williams and Pashley 1978) or a modified Moore's corer (NWRI unpublished). The cores were immediately extruded and divided into 2.0 cm sections on the shore. Samples were frozen, freeze-dried, ground, pelletized and then analyzed for major elements with X-ray fluorescence spectrometry at McMaster University in Hamilton.

For metal analysis, 1.0 g of freeze-dried and ground sediment was extracted with 10 mL of concentrated 1:1 $HCl:HNO_3$ for 16 h at room temperature. The extract was heated for 1.5 h in a waterbath at 90°C and filtered through a #44 Whatman filter. The filtrate was analyzed by atomic absorption spectrophotometry.

To determine "bioavailable" phosphorus, 10 mg of freeze-dried and ground sediment was extracted with 100 mLs of 0.5 N NaOH for 16 h at 16°C (Williams et al. 1980).

For sediment diatom analysis, between 0.01-0.02 g of freeze-dried sediment was cleaned by the hydrogen peroxide method (Swift 1967). Aliquots of 1.0 to 2.0 ml of the suspended samples were sedimented in modified sedimentation chambers (Evans 1972) and examined on a Wild inverted phase microscope at 400-1000 magnification. Identifications of the diatom valves were based on Hustedt (1930), Patrick and Reimer (1966) and Germain (1981). The sediment age was determined by the lead-210 method (Robbins and Edgington 1975).

3 RESULTS

3.1 Hydrology

The flow into Hayes Creek diminished to a low in August, 1983 and then increased greatly in September (Table 1). The flow from Hayes Creek into Chain Lake was estimated to account for about 7% of the lake outflow for the period from June 1 to October 1, 1983. During this period, the diversion flow contributed about 24% of the lake outflow. Over the study period, the lake level decreased by about 3 cm to a low in August. This decrease corresponded to 0.6% of the lake outflow. Rain falling directly on the lake represented about 4% of the lake outflow. Only 36% of the lake outflow was accounted for in the water budget.

This discrepancy in the water budget could be resolved if groundwater flow is significant. Many springs emerge from the steep mountains and flow for short distances before disappearing into a gravel layer that lines the valley.

3.2 Sources of Phosphorus

Total phosphorus in Chain Lake increased from 50 and 12 μg P/L to 150 and 110 μg P/L in the summers of 1983 and 1984 (Fig. 2). These increases of phosphorus in the lake occurred when the natural inflow had little or no flow. Moreover, the inflowing Hayes Creek and the Shinish Water Diversion contained a mean of only 18 μg P/L.

Groundwater can also be dismissed as a direct cause of the phosphorus increase in summer. The phosphorus composition of the springs varied greatly (SRP varied from 4 to 66 μg P/L), but they always contained considerably less phosphorus than the lake (Table 2). Although the springs and a headwater creek, Lee Creek, flowed from wilderness areas, the soluble reactive phosphorus concentration of three of the springs (64,54, and 37 μg/L) and Lee Creek (37 μg/L) was significantly higher than the other springs. The concentration of calcium (17-55 mg/L) and total inorganic carbon (TIC, 10-28 mg/L) in the springs also varied greatly. All but one of the springs and wells had less than 10 μg N/L of ammonia or nitrate (Table 2).

3.3 Seasonal Change in Phosphorus Concentration Reduces Effect of Water Diversion

The most striking aspect of Chain Lake was the seasonal change of phosphorus concentration (Fig. 3a). The decrease of phosphorus in November 1983 was associated with an increase of oxygen concentration from 4.4 to 8.0 mg/L. In Chain Lake, the concentration of soluble reactive phosphorus was high only if the lower water column was anoxic (Fig. 3b). At these times, the anoxic water contained more than 1.5 mg/L of iron (Table 3). The lake is shallow; thus, this nutrient rich anoxic water can readily be mixed into the surface of the lake.

3.4 Lake Sediments

The increased phosphorus concentration in the lake water in late summer was probably a result of rapid phosphorus release from lake sediments. The surface of the sediments is much higher in bioavailable phosphorus than the sediments deeper than 80 cm (Fig. 4). Although the lake water chemistry indicates that iron chemistry regulates phosphorus solubility, sediment iron was not significantly correlated to phosphorus or any other sediment parameter (Fig. 4).

Much of the phosphorus in the surface sediments is capable of entering the water column. In laboratory incubations, phosphorus was readily released into solution from surface sediments. The concentration of phosphorus in water overlying the sediment averaged 1.8 mg/L (n=9) after 20 days and 3.1 mg/L (n=3) after 40 days. After the first week, the oxygen concentrations were less than 3.0 mg/L. No hydrogen sulphide odour was apparent.

3.5 Sedimentation Rate

The rate that the lake is filling with sediment and the physical nature of the sediments are important to a management plan that may require sediment dredging.

The radiochemical dating (lead-210) indicates a mean sedimentation rate of 0.78 cm/yr. The peak of copper at 12-14 cm corresponds to the copper sulphate treatments conducted about 1967, which indicates a sedimentation rate of about 0.68 cm/yr. The peak of copper sulphate was much shallower in the central station (Fig. 5); thus, the sedimentation rate is about half that of the deeper core from near the outlet.

The surface sediments are light grey. Near 80 cm the sediments are yellowish. For unknown reasons this yellow band was formed when the railway was built around 1916. Below 80 cm the sediments gradually become light grey. The sediments have a very high water content. Above 80 cm the sediments have a high and variable water content (91-96%, Fig. 4). Below 80 cm, the sediments gradually increase in density, until about 270 cm, where the sediments increase in water content (93.8%) and then quickly become much firmer (88% water content).

3.6 Sediment Diatom Record

The sediments are a relatively pure deposit of diatomaceous earth. The freeze-dried sediments are about 50% organic carbon and 2% nitrogen. The combusted sediments are about 77% silicon dioxide.

The relative abundance (% frustules) of the dominant (>5% occurrence) diatom species in the sediment core are shown in Figure 6. The stratigraphy shows three zones: surface to 100 cm, 100-160 cm, and 178-280 cm. Radiological dating indicates that these zones formed from present to 1906, 1906 to 1861, and 1847 to 1766.

The most recently sedimented zone is dominated by *Melosira ambigua*. Frequent, but minor species are *Stephanodiscus astrea*, *Melosira italica* subsp. *subarctica*, *Asterionella formosa*, *Melosira distans* and *Cyclotella glomerata*. The presence of *Asterionella formosa* and *Fragilaria crotonensis* in samples from the surface to 38 cm indicates a transitional layer that formed 24-30 years ago. The second zone from 100 to 160 cm is dominated by *Fragilaria leptostauron*. *Fragilaria virescens* var. *capitata* is also fairly common in this zone. The deepest zone, 178-200 cm, is dominated by *Melosira ambigua*. Frequent but minor species are *Melosira granulata*, *Stephanodiscus astrea*, *Fragilaria crotonensis*, *Cyclotella glomerata* and *Melosira distans*.

DISCUSSION

The inability of the Shinish Water Diversion to suppress blue-green algal blooms is largely caused by sediment phosphorus release during a period of minimal flushing. Sediment release of phosphorus has often been reported (Bostrum and Pettersson 1982; Holdren and Armstrong 1980; Jacoby et al. 1982; Larsen et al. 1981; Lazoff 1983; Riley and Prepas 1985; Ryding 1985; Stefan and Hanson 1981a). The classic mechanism of phosphorus release from lake sediments is the release of phosphorus into solution as ferric iron is reduced in anoxic water to ferrous iron (Mortimer 1941, 1942). This reaction seems to control the water chemistry of Chain Lake.

The marked decrease in phosphorus concentration that I observed in the fall of 1983 when the lake became oxidized was also observed in an earlier study. In 1975, the soluble reactive phosphorus concentration decreased by 50% (p 55 in WIB 1977) when the oxygen concentration increased from about 4 to 8 mg/L (Fig. 3 in WIB, 1977). Similarly, the five-fold decrease in total phosphorus from the fall of 1973 to the spring of 1974 (p 34 in WIB 1977) was associated with a tripling of the oxygen concentration (Fig. 3 in WIB 1977). Presumably, the increased oxygen concentration oxidized ferrous iron to ferric iron, which then precipitated to the lake sediments with adsorbed phosphorus. The precipitation of ferric phosphate and the adsorption of phosphorus to ferric hydroxide are well established reactions (Birch 1976, Stumm and Morgan 1981).

The decreases of phosphorus concentration in the fall of 1975 and 1983 were not a reflection of enhanced flushing. Less than 5% of the lake was discharged during these periods of phosphorus decrease. The precipitation of phosphorus with iron during high flow periods minimized the effect of the diversion and presumably enhanced the retention of phosphorus. The lake inlets have high iron concentrations thereby providing ample reactant for phosphorus precipitation (Table 3; $\bar{x}$ of 350 µg/L in Hayes Creek, 1.25 mg/L in Shinish Water Diversion, WIB 1977).

Little of the sediment phosphorus would be permanently adsorbed to iron because more than half of the iron was converted to pyrite (Manning unpublished). The formation of pyrite should solubilize phosphorus which then could move up the sediments with groundwater (Van Liere and Mur 1982). This sequence of events would produce the large increase of phosphorus observed in the surface sediments (Fig. 5) and the lack of an iron-phosphorus correlation in the sediments.

Although some uncertainty exists about the proportion of soluble reactive phosphorus released from sediments that is biologically available (Nurnberg and Peters 1984), in Chain Lake the release of phosphorus from the sediments appeared to initiate the algal blooms.

The hypothesis that groundwater and sediment interactions are responsible for the eutrophication of Chain Lake can be supported by several studies. The indirect estimate of groundwater flow into Chain Lake agrees well with groundwater measurements at a nearby site, the Trapping Creek Basin (Lawson

1967). Both sites have similar rainfall, physical relief, and geology (granite and granodiorite). At Trapping Creek, 31 of the 56 centimeters of rainfall flowed as groundwater. This estimate of 55% of water flow occurring as groundwater agrees well with my estimate of 64% obtained by difference from the Chain Lake water budget.

Moreover, the water and phosphorus budgets indicate that the direct loading of human wastes could not produce the summer peak of phosphorus. The number of people required to produce this increase of phosphorus would be an order of magnitude more than ever stayed near the lake. The average occupancy in summer is near thirty. The average phosphorus loading from sewage is 1 kg capita^{-1} year^{-1} (Allum et al. 1977). The August 1983 increase in phosphorus in the lake was about 4.4 kg/day (equivalent to 1600 people living on the lake).

The phosphorus budget also indicates that most of the phosphorus loading is natural. For example, the export of phosphorus from Chain Lake in the summer of 1983 was equivalent to the yearly excretion of 188 people (Table 4). This calculation overestimates the number of residents by an order of magnitude. Weathering of the apatite rich rock (Cockfield 1947,1948; Rice 1946) appears to be the main source of phosphorus, and groundwater flow is the main route of phosphorus entry to the lake.

The sediment diatom stratigraphy also supports the hypothesis that Chain Lake was eutrophic hundreds of years before cottages were built. The two most common diatoms in sediments about 220 years old, Melosira ambigua and Melosira granulata are found in eutrophic waters (Stoermer et al. 1985, Germain 1981). The surface sediments are also dominated by Melosira ambigua.

The diatom stratigraphy indicates that water quality varied quickly. In the deepest sediments, Fragilaria crotensis was also found. This diatom is usually found in mesotrophic to oligotrophic waters (Stoermer et al. 1985, Germain 1981, Nalewajko et al. 1981). In the surface sediments, the presence of Melosira italica subsp. subarctica and Melosira distans indicates oligotrophic waters (Stoermer et al. 1985, Skogheim and Erlandsen 1984). Presumably, the lake was only eutrophic during the periods of phosphorus release from the lake sediments, as has occurred in recent years.

The sediment diatom stratigraphy indicates that the first dam that was built by the first settlers about 1906 greatly changed the lake. Before construction of the first dam, the sediments which are now at 100-160 cm were dominated by Fragilaria leptostauron. This diatom is usually found in shallow water, often growing on mud surfaces (Patrick and Reimer 1966). The construction of the second dam in 1957 had a subtle effect on the diatom composition; two new species began to grow.

The sediment diatom stratigraphy indicates that the water diversion had no effect on the diatom composition. This observation confirms that the diversion has a minor effect on eutrophication. The diversion's only effective function is to maintain water levels.

The phosphorus budget indicates that to flush phosphorus faster than the sediment release rate (Table 4), the diversion would have to be enlarged at least three fold. The effect of such an expensive project on eutrophication and fisheries is not certain. In this shallow lake a suppression of phytoplankton growth may enhance macrophyte growth. To avoid ice damage to the flumes, the diversion only flows in the summer; thus, the winter oxygen concentration and fish survival may not be improved by a larger diversion.

The diversion may be useful in a program of hydraulic dredging to at least maintain water levels and perhaps to reduce eutrophication. Prior to dredging, the lake level could be dropped by closing the diversion and opening the dam; thus, suspended sediment would not foul the outflow stream bed. After dredging, the diversion could restore lake levels with minimal disruption.

Chain Lake needs a long-term management program utilizing sediment dredging. Eventually, some dredging will be required to maintain the lake; the dam can not be raised again. To maintain the present water volume, about 2,350 m^3 of sediment must be dredged each year.

A dredging program that removed surface sediments would reduce or prevent an increase in eutrophication. Several observations indicate that the surface sediments would move into the dredged basin for subsequent removal: 1) Earlier bathymetric maps (Northcote 1967) differ in major ways from data collected in 1986 (Fig. 1). 2) The erratic distribution of Pb-210 in the surface 40 cm of sediment indicates a reworking of the sediment (Fig. 3). 3) The copper data indicates enhanced sedimentation at the outlet end of the lake (Fig. 5). 4) The surface 2 cm of sediment is 97% water and 3% diatom frustules which should move with little energy. 5) Gale force storms that blow along the valley leave the lake turbid by resuspending lake sediments.

Once loose surface sediment moved into the hole, then the best solution would be to put a pipe into the hole and pump out the loose mud; this dredging scenario is implemented in marine estuaries (Van Oostrum and Parker 1980).

Large movement of sediment would occur only after a major storm. For most of the time the basin could function as a fish refugia that would reduce summer fish kills. The outlet end of the lake is a suitable site in that it is near the entry of the cold sub-alpine diversion water. Without including a factor for the thermal structure that would be imposed by the cold diversion water, the dredging of a basin two meters deeper in Chain Lake, should produce a stratified water column with a cold oxidized hypolimnion (Stefan and Hanson 1981b).

This proposal may have relevance to many reservoirs in western North America but its potential may be greatest in the interior of British Columbia where water diversions are used primarily to control water level, where eutrophication is a problem, and where sedimentation of diatoms is filling lakes.

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Figure Legends

1 Chain Lake. Depth contours are in meters. CAMP = campground. S = sampling site.

2 Figure 2. Total phosphorus concentration in Chain Lake.

3 a) The soluble reactive phosphorus concentration at 1.0 m in Chain Lake. b) The oxygen concentrations in Chain Lake.

4 Chain Lake sediment chemistry.

5 Copper concentrations in two sediment cores.

6 Diatoms in the sediments of Chain Lake.

TABLE 1: Hydrology - 1983

Date	Flow (L/sec)	TP (μg/L)	$\overline{X}$ - Flow (L/sec)	$\overline{X}$P - Flow (mg/sec)	H_2O - Loss ($m^3 x 10^3$/month)	P Loss (Kg/month)
Outflow						
June 10	132	30	121	6.5	314	16.9
15	102	47				
23	130	83				
July 8	117	38	108	4.2	289	11.3
21	102	45				
26	111	33				
Aug 23	72	60	66	16.5	177	44.2
31	60	478±80				
Sept 19	487	92±16	487	44.8	1304	116
28	814*	108				
					2084	188
Diversion						
June 10	33.8	12	31	0.39	80	1.0
15	30.7	12				
23	28.5	14				
July 8	41.7	13	33	0.71	89	2.4
21	50.3	28				
26	7.8	24				
Aug 31	37	22	37	0.81	99	2.8
Sept 19	91.5	18	91.5	1.65	237	4.3
					505	10.5
Natural Inlet						
June 10	46	19	30	0.67	77	1.8
15	21	24±6				
23	23	28				
July 8	19	21	24	0.89	65	2.4
21	24	52				
26	30	34				
Aug 23	no flow					
31	no flow					
Sept 1	no flow					
19	no flow					
21	no flow					
					142	4.2

* secondary outlet was opened. This discharge was not included in the water budget.

P - Phosphorus

$\overline{X}$ - Arithmetic mean

TP - Total phosphorus

Table 2 Chemistry of Springs

Chain lake Sites-#	Ca	Mg	Na	K	SRP	TIC	NH_3	NO_3	Cl	SO_4
G. Smith					4	10				
Suggets	37.2	6.3	5.6	2.5	66	24	4	3	1.0	0.5
Suggets Jr	23.5	4.3								
Wellburn	54.7	8.8	7.8	1.9	8	28	158	9	1.4	0.5
Banks	41	9.8	6.9	4.0	37	26	6	2	0.9	0.5
Maurer	17	4.0	10.2	2.6	54	14	2	3	1.4	3.6
D. Smith	25	5.1	11.3	2.6	28	20	2	4	0.8	7.9

Soluble reactive phosphorus (SRP) dissolved organic nitrogen (DON), ammonia (NH_3), and nitrate (NO_3) are in units of $\mu g\ L^{-1}$. All other data are in units of $mg\ L^{-1}$. The pH of the springs was 6.9.

Table 3 Iron concentrations in Chain Lake - 1984

Depth (m)	Iron Concentration ($\mu g/L$) July 6	July 16	Aug 10	Sept 14
1	426	377	236	252
2			322	633
3	264	379	812	1525
4			784	777
5	385	654	1967	741
Inlet	893	219		

Table 4 Phosphorus Budget for Chain Lake

Summer of 1983		Annual
<u>Inflow</u>		
Diversion	10.5	10.5*
Hayes Creek	4.2	278.**
Springs#	70.9	319.***
Internal Loading##	406	406
Sediment###	1966	
<u>Outflow</u>	188	438.****

All values are kilograms of phosphorus.

Springs apparently contributed 64.2% of the flow. Mean SRP of the springs was 30 µg/L.

Internal loading was calculated from the increase in phosphorus in the lake plus the outflow.

The pool of phosphorus available for exchange with the surface water was calculated from the difference in the bioavailable phosphorus in the surface 2 cm from the amount of bioavailable phosphorus in the sediment at 2-4 cm.

* The diversion only flows for the summer period.

** We assumed that the rest of the inflow had the same mean phosphorus as summer values (29.7 µg/L) and we used the flow from WIB (1977).

*** We assumed that groundwater had the same flow yearly as it had in the summer.

**** We assumed that the outflow had the same phosphorus concentration as the lake had prior to the algal blooms and we used the WIB (1977) hydrology.

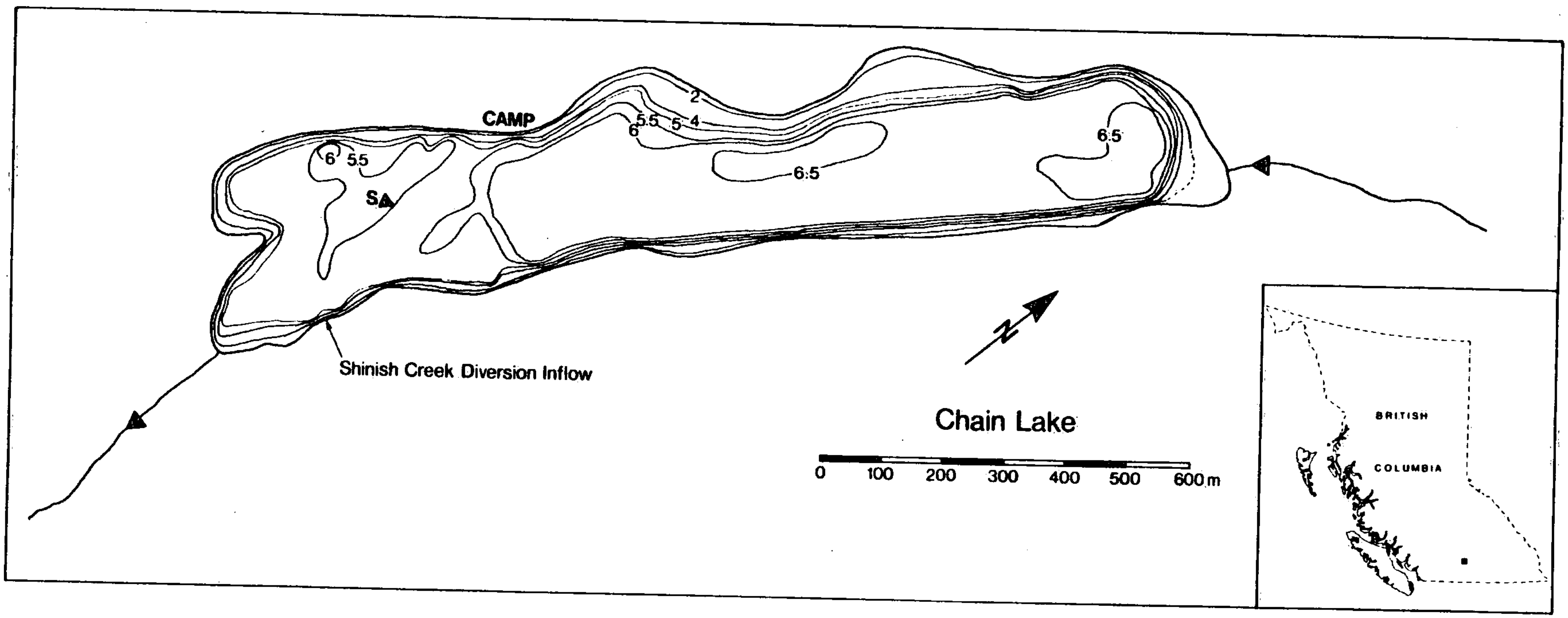

Figure 1 Chain Lake. Depth contours are in meters.

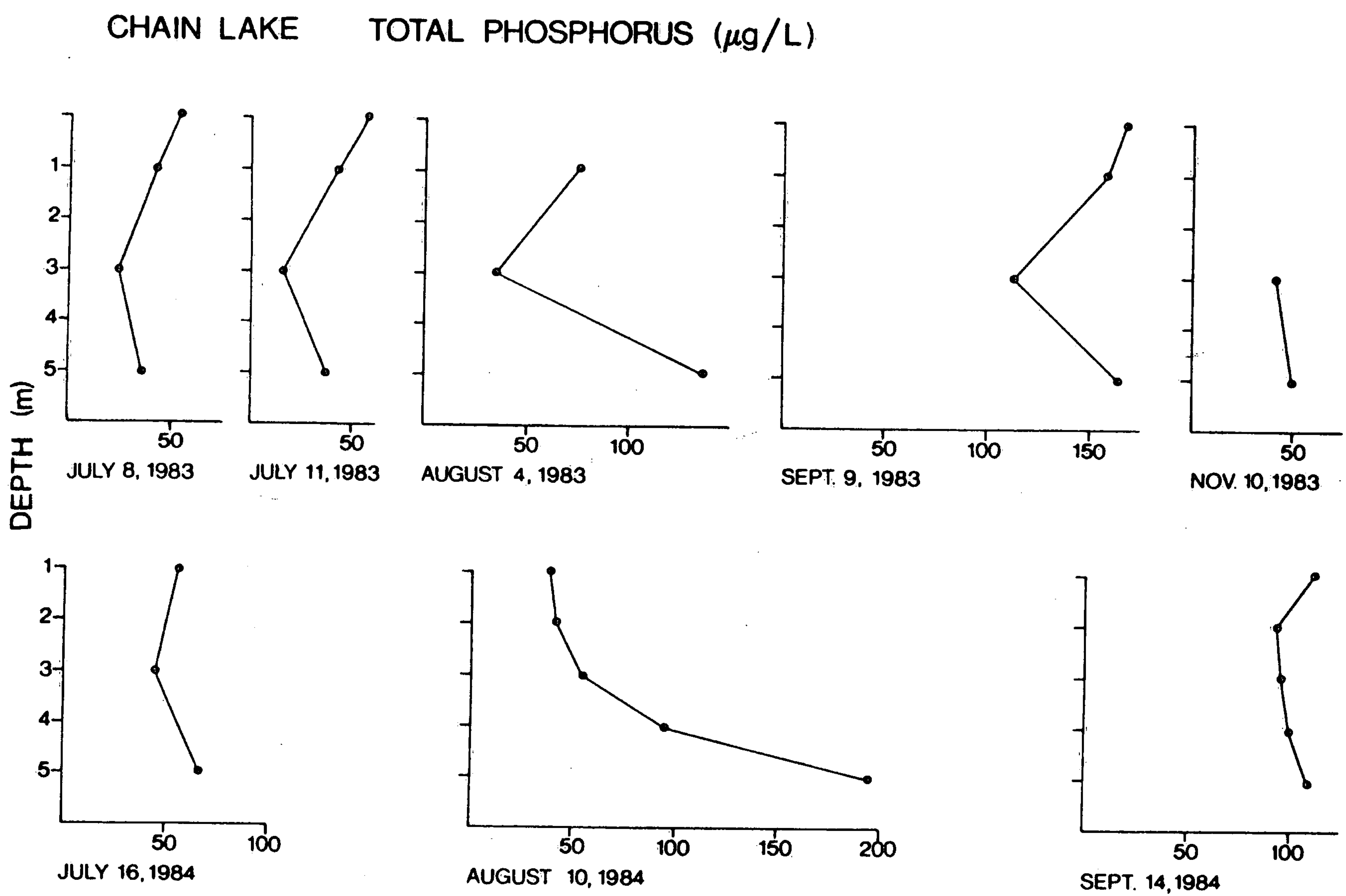

Figure 2 Total phosphorus concentration in Chain Lake.

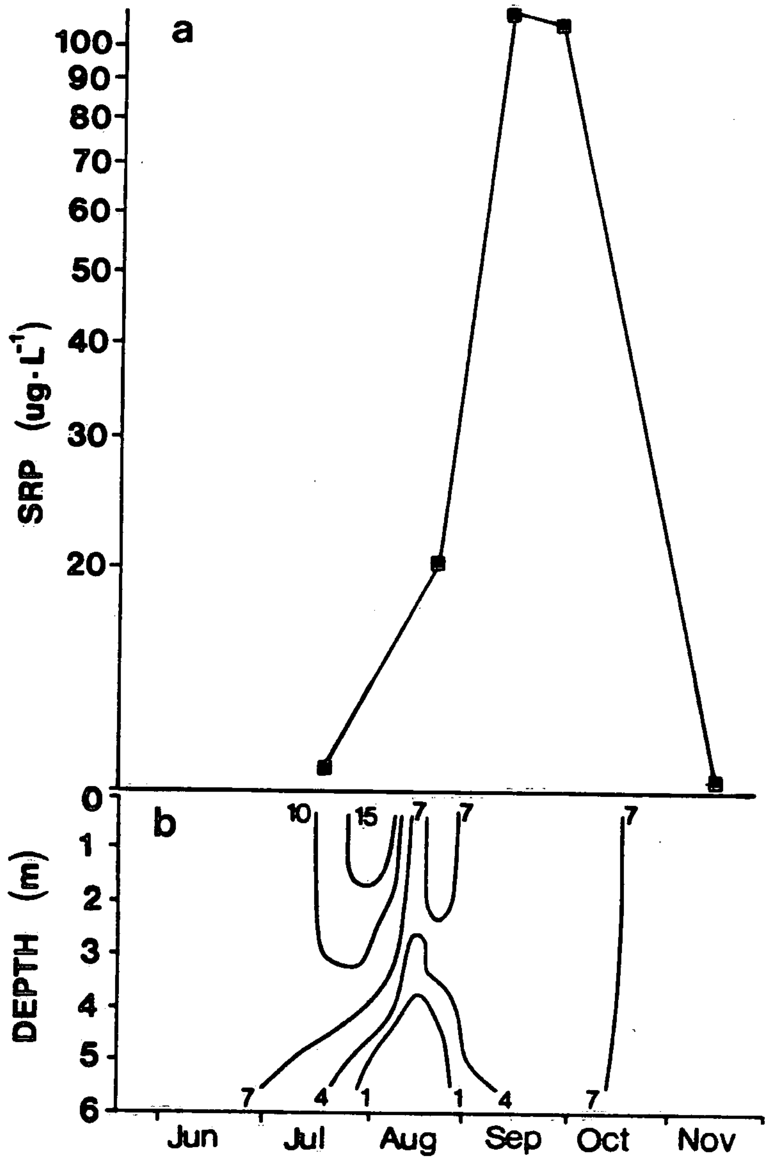

Figure 3.

a) The soluble reactive phosphorus concentration at 1.0 m in Chain Lake.

b) The oxygen concentrations in Chain lake.

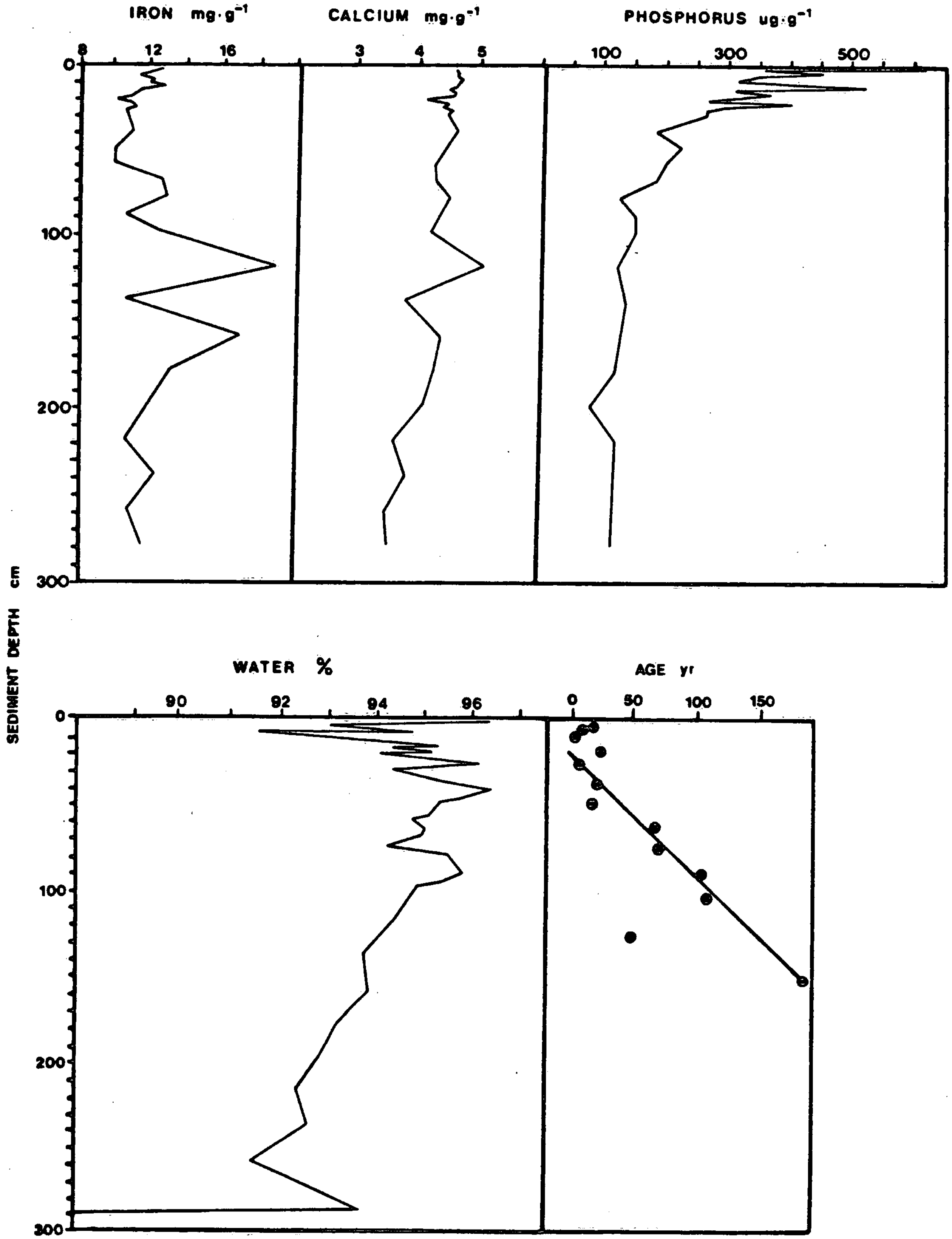

Figure 4. Chain Lake sediment chemistry.

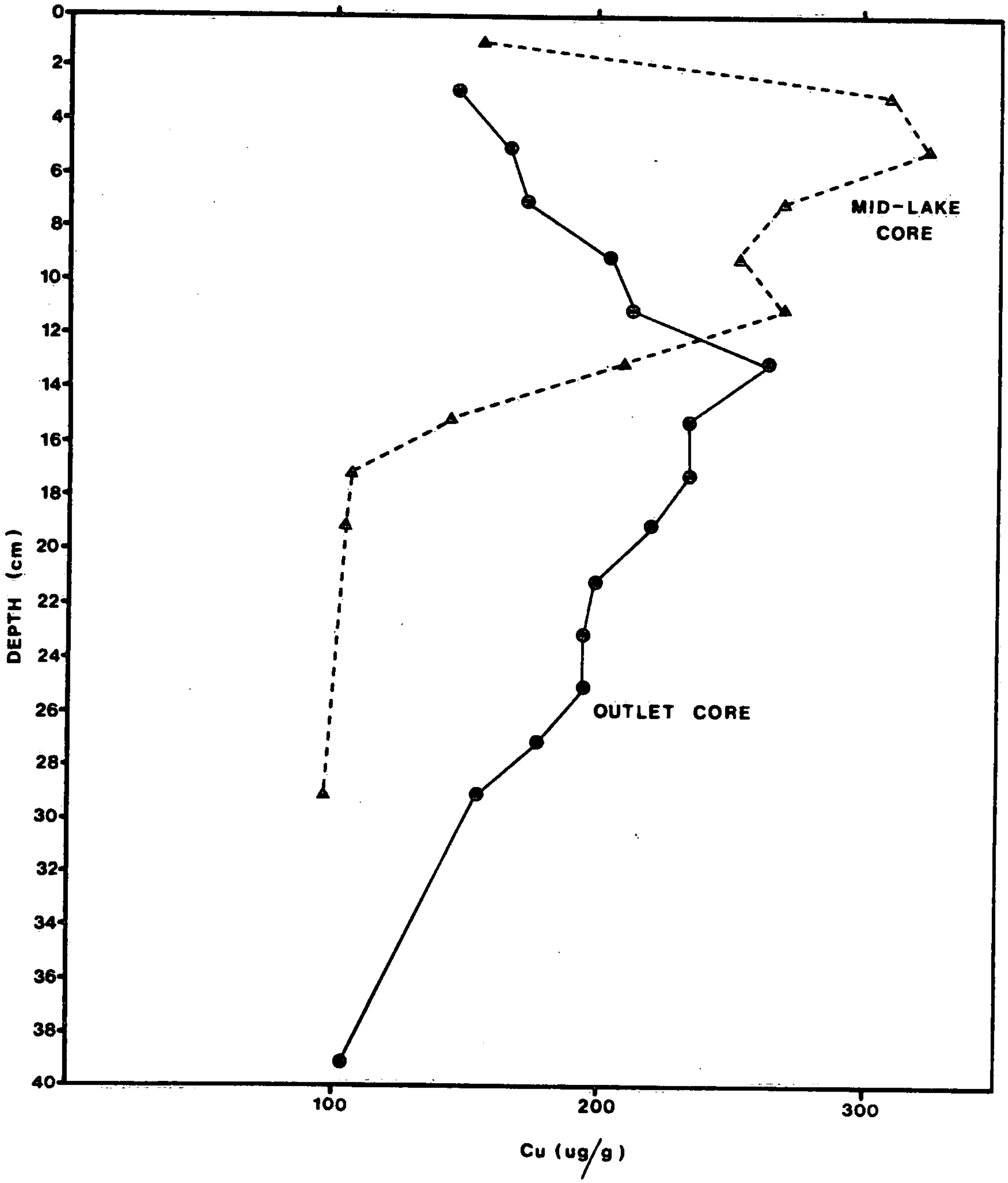

Figure 5. Copper concentrations in two sediment cores.

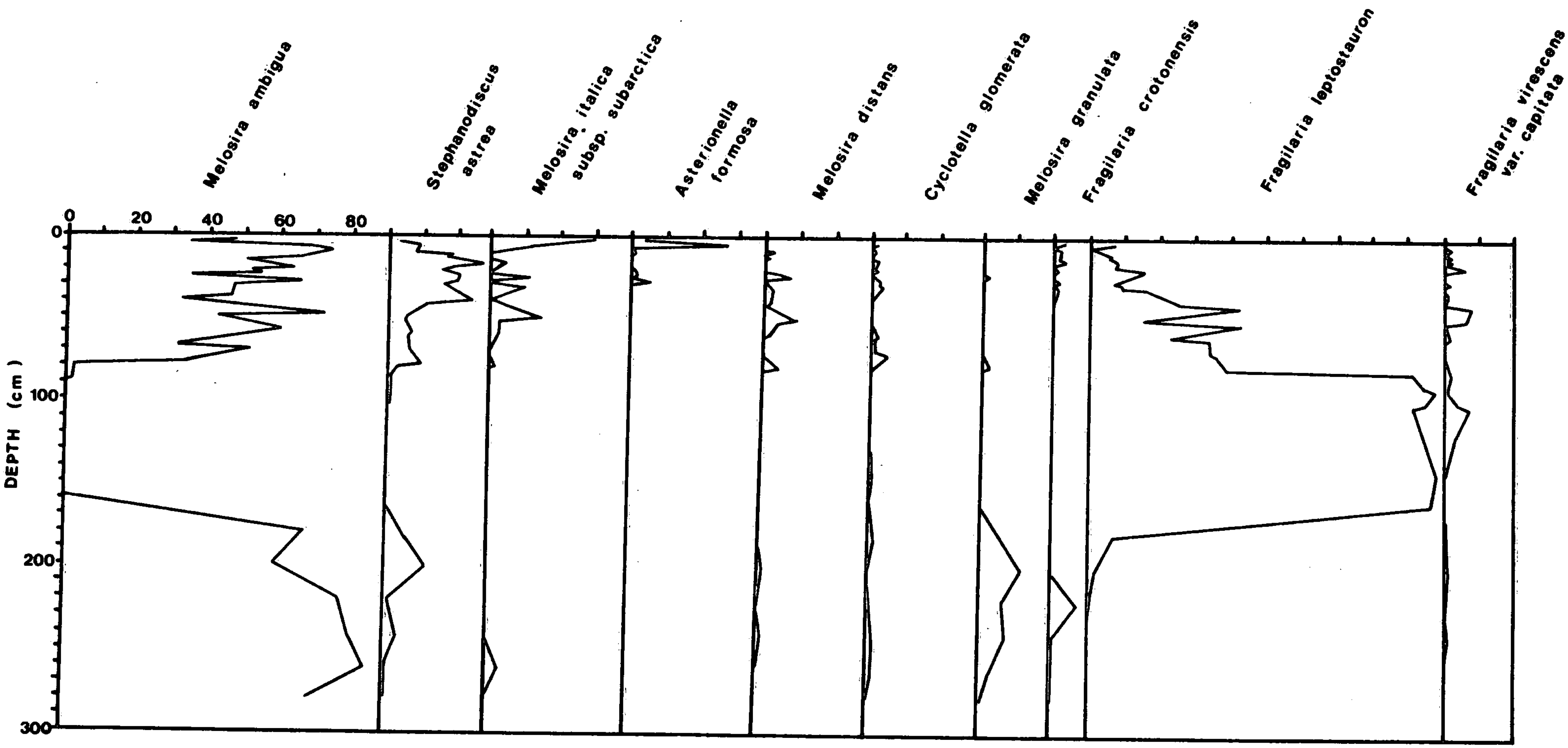

Figure 6. Diatoms in the sediments of Chain Lake.