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Diatom Indicators of Fluctuations of Eutrophication and Water Levels in Chain Lake, British Columbia

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Management Perspective

Studies of diatoms, a type of algae, in a 13-metre sediment core provide insight into both the history of eutrophication and water levels of Chain Lake. Chain Lake is a naturally eutrophic lake about 40 km north east of Princeton, British Columbia.

The deepest sediments show that the lake was eutrophic several thousand years ago but later the productivity of the lake oscillated as water levels changed. A series of droughts began about 6000 years ago. The lake level decreased, the sediments became oxidized, sediment release of phosphorus was reduced, and eutrophication was suppressed. When the climate became wetter, the lake level increased. After at least several decades, sediment phosphorus release again enhanced eutrophication. We observed five diatom fluctuations consistent with droughts and there were likely at least ten droughts.

The response to natural perturbations suggests constraints to several management plans and helps select techniques to manage the lake. At present, source control of nutrients is not cost-effective. The nutrient loading from local cottages is relatively unimportant. Any lake treatment, such as bottom water withdrawal, that results in more oxygenation of the sediments should decrease eutrophication of Chain Lake. If the greenhouse effect results in a new drought, the existing water diversion into Chain Lake would be required to maintain water levels. In this area, fish can not survive the winter and macrophytes can be a problem in shallow lakes.

PERSPECTIVES DE GESTION

L'étude des diatomées, type d'algues, dans une carotte de sédiments de 13 mètres, permet de voir l'histoire de l'eutrophisation et du niveau d'eau du lac Chain, formation eutrophique naturelle à environ 40 km au nord-est de Princeton, en Colombie-Britannique.

Les sédiments les plus profonds montrent que le lac était de nature eutrophique il y a déjà plusieurs milliers d'années, mais, plus tard, la productivité du lac a oscillé avec les variations du niveau d'eau. Il y a environ 6 000 ans commence une série de périodes de sécheresse; le niveau du lac baisse, les sédiments sont oxydés et libèrent moins de phosphore, l'eutrophisation est supprimée. Lorsque le climat redevient plus humide, le niveau du lac augmente de nouveau. Après au moins plusieurs décennies, la libération de phosphore par les sédiments active de nouveau l'eutrophisation. Nous avons observé cinq fluctuations de diatomées coïncidant avec des périodes de sécheresse, et il y avait probablement au moins dix périodes de ce type.

La réaction aux perturbations naturelles facilite le choix de méthodes de gestion pour le lac et montre que des contraintes s'imposent dans plusieurs plans de gestion. Actuellement, l'élimination des agents nutritifs à la source n'est pas rentable. La charge de ces agents provenant des habitations de l'endroit est relativement peu importante. N'importe quel traitement, comme l'extraction d'eau de fond, qui entraîne une plus grande oxygénation des sédiments, devrait pouvoir diminuer l'eutrophisation du lac Chain. Si l'effet de serre provoque une nouvelle sécheresse, la déviation d'eau vers le lac Chain deviendrait nécessaire pour maintenir le niveau d'eau. Les poissons risquent de ne pas survivre à l'hiver et les macrophytes peuvent devenir un problème dans des lacs peu profonds.

Abstract

Diatom studies of a 12.6-metre piston core indicate that eutrophication of Chain Lake has fluctuated in response to a deposit of volcanic ash and changes in water level. In the bottom sediments, the dominate diatom, Melosira ambigua indicates the lake was eutrophic. After the Mazama ash layer, the lake was dominated by the diatom Melosira distans that indicates low productivity. Higher in the sediments the diatoms oscillated between eutrophic and oligotrophic indicators. The lake was less productive after periods of low water level, as indicated by the dominance of the littoral diatom Fragilaria leptostauron. At least five times, the lake level was low and the climate was presumably drier. Corresponding sediment layers have relatively high concentrations of phosphorus.

Pyrite formation results in as much as 60% of the iron in sediments being unable to complex phosphorus. Phosphorus appears to have migrated up the sediment producing relatively high surface concentrations of phosphorus. Presumably the fluctuations in water level resulted in changes in oxygenation of the sediments, changes in rate of pyrite formation and in turn eutrophication.

Résumé

L'étude des diatomées d'une carotte de 12,6 m (obtenue par piston) montre que l'eutrophisation du lac Chain a fluctué après le dépôt de cendres volcaniques et les variations dans le niveau d'eau. La diatomée dominante dans les sédiments de fond, *Melosira ambiqua*, montre que le lac était eutrophique. Après la cinérite de Mazama, *Melosira distans* était la diatomée dominante, ce qui révèle une faible productivité. Plus haut dans les sédiments, les diatomées oscillaient entre les indicateurs eutrophiques et oligotrophes. Le lac était moins productif après les périodes de bas niveau d'eau, comme l'atteste la prédominance de la diatomée littorale *Fragilaria leptostauron*. Le niveau du lac a été bas au moins à cinq reprises, et on suppose que le climat était alors plus sec. Les couches de sédiments correspondant à ces périodes renfermaient des concentrations relativement élevées de phosphore.

Conséquence de la formation de pyrite : jusqu'à 60 % du fer présent dans les sédiments ne pouvait former de complexe avec le phosphore. Ce dernier semble avoir progressé dans les sédiments avec, comme résultat, des concentrations relativement élevées de phosphore en surface. Il est probable que le niveau d'eau a modifié l'oxygénation des sédiments et la vitesse de formation de la pyrite, ce qui à son tour a provoqué des changements dans l'eutrophisation.

Chain Lake is located at an elevation of 1007 m on the Thompson Plateau in the interior Douglas fir biogeoclimatic zone (Fig. 1, Murphy 1987). It is in the rainshadow of the Cascade Mountains; thus, the valleys are semi-arid. Chain Lake receives a mean of 53 cm of rain per year and extreme droughts of three months without rain have been recorded (Environment Canada 1971). To provide water storage for irrigation, a dam of 1-2 m was built on the lake outlet about 1915 and it was raised 1.2 m in 1957.

Part of the Shinish Creek was diverted into Chain Lake in 1968 to reduce eutrophication. Dense blue-green algal blooms continue to form each summer and at times fish kills have occurred. Calculations used to design the diversion did not include a groundwater flux of phosphorus or sediment phosphorus release. The bedrock is a Jurassic volcanic intrusion that is rich in the phosphate mineral apatite (Cockfield 1947, Rice 1946), and the dissolved phosphorus concentrations of the springs in the valley are as high as 50 μg/L (Murphy 1987). The sediment phosphorus release in August 1983 was approximately 10 mg m^{-2} d^{-1} (Murphy 1987).

Studies of a 2.88 m sediment core indicated three significant changes in the diatom composition (Murphy 1987). Recent sediments (0-80 cm) and sediments 180-288 cm deep were dominated by <u>Melosira ambigua</u> and other diatoms which are indicators of eutrophication (Germain 1981, Stoermer et al. 1985). The middle section of the core was primarily composed of <u>Fragilaria leptostauron</u>, a benthic diatom (Patrick and Reimer 1966). Lead 210 analysis confirmed that the switch from <u>Fragilaria leptostauron</u> to <u>Melosira ambigua</u>

coincided with the construction of the dam on the lake outlet about 1915.

The insights from the 2.88-m core should facilitate interpretation of the paleolimnology of the deeper sediments of Chain Lake. For example, the presence of _Fragilaria leptostauron_ and _Melosira ambiqua_ deeper in the sediments should indicate droughts or eutrophication, respectively. In this study, we studied the diatom composition of a 12.6-m piston core. As well as the general interest in paleolimnology there were two applied objectives: 1) will the water diversion be required to maintain lake levels? and 2) has the lake become more eutrophic?

Methods

A piston core was collected October 21, 1988 with a corer designed by McKean and Nordin (1986). The core was subdivided into 10-cm sections, placed on ice, and shipped to the National Water Research Institute (NWRI) for freeze drying. Except for biogenic silica and pyrite analyses, other diatom and chemical analyses are similar to earlier studies (Murphy 1987). The equipment used to collect the piston core and the high water content of the surface sediments (>95%) resulted in mixing of the surface 1-2 m of sediment. To provide better resolution, all presentations of the 10 m of sediment are composites of the 2.88 push core (Murphy 1987) and the sediments of the piston core deeper than 2.88 m.

Biogenic silica was measured using minor derivations of the techniques of Schelske et al. (1985). Freeze-dried sediment samples (20-25 mg) were weighed into 125-ml round polypropylene bottles and 40 ml of 5% Na_2CO_3 was added. The bottles were placed in an 85°C water bath for 5 h. After 3, 4, and 5 h of leaching, 1.0 ml aliquots were extracted and analyzed for dissolved silica using the reduced molybdosilicic acid spectrophotometric method (Strickland and Parsons 1968, DeMaster 1981). A regression of percent silica extracted over time was extrapolated to time zero to determine biogenic silica content. The following minerals were analyzed in the biogenic extraction procedure to ensure that other silicates were not extracted; albite, biotite, kaolinite, labradorite, muscovite, and oligoclase.

Samples for pyrite and Pb-210 analyses were collected with a Tech Ops corer (Mawhinney 1987). The pyrite content of the unground, freeze-dried sediment was determined by Mössbauer spectrometry (Manning et al. 1988). The rates of sediment accumulation in Chain Lake were determined by Pb-210 radiochemical dating (Robbins and Edgington 1975). Determination of minerals present in subsamples was carried out qualitatively by a Philips X-ray diffraction spectrometer.

The diversity index of the diatoms was measured with MacArthur's index, the reciprocal of Simpson's index (Peet 1974). The equation is $D = 1 / \Sigma [n_i(n_i - 1)] / [N(N-1)]$ where n_i is the number of individuals in species i and N is the total sample size. Calculations were done with Lotus 123. Graphs were done with Lotus 123 and Corel Draw.

Results

Diatom Record

Except for the Mazama ash layer, the sediments are a relatively pure diatomaceous earth deposit. The Mazama ash layer was exceptional in several ways. Unlike our inorganic standards, the ash extracted as if it was biogenic silica. Less than 5% of the inorganic silica standards reacted as biogenic silica. The exceptionally low organic carbon, nitrogen and loss on ignition of the volcanic ash confirms visual observations that the ash has a low diatom content (Fig. 2).

The diatom record is unusual in and above the volcanic ash layer. Stephanodiscus hantzchii was the dominant algae in the volcanic ash (37.5%) but it was not important (>5%) above the ash and it comprised only 12÷15% of the diatoms in a few samples below the ash. Immediately above the volcanic ash, more than 29% of the diatoms were Melosira islandica, a diatom indicating cold water. Two minor peaks of Melosira islandica (8-10%) occurred both before and after the ash deposit.

The rest of the diatom record is also complex. Fifty-five species were identified. In many samples, diatoms that indicate both eutrophic and oligotrophic conditions were found. Some of the complexity of the data can be eliminated by focusing only on the samples dominated by more than 25% of either Melosira ambiqua or Melosira distans, indicators of eutrophic and oligotrophic waters, respectively (Fig. 3). At the bottom of the core, five samples consistently indicate eutrophication. The fall of the volcanic ash resulted in a shift to oligotrophic conditions. The lake remained oligotrophic for about 85 cm (about 1000 y) before a series of oscillations between eutrophic and oligotrophic conditions occurred. The more recent sediments (about 300 y) contain diatoms indicating either eutrophic or low water level conditions.

Fragilaria leptostauron, a benthic diatom is a good indicator of low water levels. It became the dominant diatom when the sediment record indicates a switch from the dominance of *Melosira ambigua* to *Melosira distans*. These inferred switchs between eutrophic and oligotrophic conditions in the middle of the core are matched by three peaks of *Fragilaria leptostauron* (Fig. 4).

The diversity index of diatoms is highest at the bottom of the sediment core, decreases to a minimum at about 80 cm from the sediment surface and increases slightly towards the surface (Fig. 5). The diversity of diatoms is highly variable but most of the extremes are associated with diatoms that are known indicators of either eutrophic, oligotrophic or dry conditions.

The dominance of *Fragilaria leptostauron* is associated with pronounced changes in the sediment chemistry. With a few exceptions, major peaks in sediment phosphorus concentration are associated with a diatom community composed of at least 25% *Fragilaria leptostauron* (Fig. 4). The concentration of phosphorus is significantly, albeit weakly correlated to the concentration of *Fragilaria leptostauron* ($r = 0.41$, $P > 0.01$, $n = 40$).

The major exception in the phosphorus/*Fragilaria leptostauron* relationship is the phosphorus peak associated with the bottom of the Mazama ash. Another exceptional sample is one dominated by Cyclotella meneghiniana (767-777 cm, 57%) that contained a high bioavailable phosphorus content. This sample 30 cm below the Mazama ash was in the hypsithermal period. Only three other samples contained significant concentrations of this diatom (1001-1011 cm, 16%; 808-818 cm, 9.9%; 598-608, 24%) and they all contained high concentrations of Fragilaria leptostauron (24, 23 and 37%, respectively). It is highly likely that Cyclotella meneghiniana is also an indicator of low water levels.

Dating/Stratigraphy

Radiocarbon dating was attempted but the high concentration of ^{238}uranium interfered with the analysis. The presence of uranium in the sediments indicates that groundwater is flowing through the sediments. Uranium is soluble in oxidized groundwater; the groundwater is oxidized and it contains up to 66 μg/L of uranium (Murphy and Joshi unpublished). Uranium adsorbs to silica and organic matter, especially in anoxic environments (Benson and Leach 1979).

The most obvious visual/tactile marker is a thick layer of volcanic ash at 706 cm from the sediment surface. The ash has a fine texture and is relatively thick (25 cm). Mazama ash is the only known local ash deposit with these features (Powers and Wilcox 1964, Westgate et al. 1974, Nesbitt 1974). Also, the position of the Mazama layer in the core collected by Mack et al. (1978) 200 km south southwest is approximately the same depth as the ash layer in

Chain Lake; the core collected by Mack et al. (1978) is also approximately the same length as the Chain Lake piston core. The Mazama ash fell during the "Thermal Maximum" approximately 6600 years ago (Frywell 1965).

Two other dates can be used to quantify sediment rate. The bottom of the sediment core should be about 9600 B.P. (mean of 10000 B.P. from Fulton (1969), 8410 B.P from Alley (1976), and 10500 B.P from Mack et al. (1978)). Clay streaks were observed 70 cm from the bottom of the core; they presumably were from post glacial deposits. The Pb-210 sedimentation rate was measured on 13 samples (Murphy 1987); sediments 140 cm from surface are approximately 150 B.P. The sedimentation rate of three zones can then be calculated with measurements of solids content from the piston core (5%, 12% and 16% solids, respectively, from top to bottom, Fig. 6).

The surface zone (0-140 cm, surface to Pb-210 marker) has a sedimentation rate of 9.3 mm y^{-1} or 47 mg cm^{-2} y^{-1}. The middle zone (140-706 cm, Pb-210 to Mazama ash) has a sedimentation rate of 0.88 mm y^{-1} or 10.5 mg cm^{-2} y^{-1}. The bottom of the piston core (706-1257 cm, Mazama ash to bottom) has a sedimentation rate of 0.83 mm y^{-1} or 9.33 mg cm^{-2} y^{-1}.

The carbon and nitrogen content of the sediments decreases deeper in the core (Fig. 2). The biogenic silica content of the sediments is relatively conservative (Fig. 2), and the sedimentation rate of biogenic silica should be a better estimate of historic algal production than total sedimentation rates. The biogenic silica sedimentation rates of three zones is: surface 15.2 mg cm^{-2} y^{-1}, middle 5.46 mg cm^{-2} y^{-1}, bottom 5.42 mg cm^{-2} y^{-1}.

Mössbauer Analysis

Mössbauer analysis of the surface sediments indicates that iron is present in the forms of ferric iron, ferrous iron, and pyrite (FeS_2) in the following respective concentrations of 60%, 20%, and 20%. Deeper in the core the concentration of pyrite increases. At 40 cm from the sediment surface approximately 60% of the iron is present as pyrite (Fig. 7). The presence of pyrite was confirmed by optical microscopic detection of opaque pyrite framboids and by x-ray diffraction patterns.

The concentration of ferrous iron decreases from the surface concentration of approximately 20% to 15% at 40 cm. The percent of ferric iron decreases from a high of 60% at the sediment surface to 30% at 40 cm from the sediment surface. The relatively slow reduction of ferric iron indicates that much of the ferric iron is metastable in anoxic sediments. Most of the ferric iron is probably x-ray amorphous or poorly crystallized hydrated ferric oxide. Conversion of ferric iron into pyrite is indicative of strongly reducing conditions generated by microbial decompostion of organic matter in sediments.

Discussion

The diatom composition of the sediments indicates that the lake is naturally eutrophic but large variations in the degree of eutrophication have occurred. The volcanic ash and droughts appear to have reduced eutrophication and resulted in peaks of phosphorus in the sediments. The environment that would produce these sediments would be more oxidized, with less pyrite formation and hence greater sediment ability to bind phosphorus.

The Mazama ash layer is known to act as a major groundwater aquifer (Nesbitt 1974) and the groundwater observed in springs near Chain Lake is oxidized. The distinct peak of phosphorus at the bottom of the Mazama ash layer contains more phosphorus than the Mazama ash found in other areas (0.09%, Powers and Wilcox 1964). The P-peak in the Mazama ash in Chain Lake presumably represents precipitation of phosphorus moving up from anoxic sediments into an oxidized layer.

The duration of the suppression of eutrophication by the Mazama ash is masked by the presence of droughts. The dominance of Fragilaria leptostauron and the inferred droughts results in higher phosphorus concentrations in the sediments and a subsequent reduction in eutrophication.

The middle and bottom sediments of Chain Lake are significantly different from the surface sediments. Unlike the deeper sediments, the indicator of oligotrophic water, Melosira distans is relatively rare in the surface sediments. In the 2.88-m core, Melosira distans is less than 3% of the bottom diatoms, absent in the middle zone, and less than 8% of the diatoms after the dam was raised (Murphy 1987). New diatom indicators of eutrophication, _Asterionella formosa_ and _Melosira granulata_, were found in the 2.88-m core, but not deeper in the sediments. Also, the sedimentation rate of biogenic silica is three times higher in the surface sediments.

The reduction in diatom diversity also indicates greater eutrophication in the last 300 years. In general, a less diverse algal community reflects a more eutrophic environment (Peet 1974). The reduction in diversity and increase in eutrophication occurred as the lake filled and lost its hypolimnion.

The extremes of a deep stable hypolimnion (up to 13 m deep) or no hypolimnion would have resulted in trapping of phosphorus in the hypolimnion or sediments, respectively. As exists now, the intermediate water levels with shallow weakly stratified hypolimnia result in enhanced recycling of phosphorus. Calm weather results in a stratified anoxic water over the sediments and sediment phosphorus release occurs. In most storms, the lake mixes and dense algal blooms occur.

Confirmation of this hypothesis can be found in the dredging studies of the Fairmont Lakes which are similar in size to Chain Lake. In models of these lakes, Stefan and Hanson (1981) predicted that dredging to 8-9 m would reduce eutrophication by reducing phosphorus transport to the photic zone. Three lakes were dredged less than the designed depths. The shallow hypolimnia that were created resulted in enhanced sediment phosphorus release and more algal growth (Hanson and Stefan 1984).

Future research should determine if Mössbauer or other chemical analyses could determine the mechanisms or reactions that lake level regulates. Further work would likely show that pyrite formation is the dominant reaction blocking the ability of iron to complex phosphorus in all sediments with indicators of eutrophication. The presence of iron-phosphorus compounds in sediments indicating oligotrophic conditions has not been demonstrated. Further insight into the reactions may facilitate management of shallow lakes like Chain Lake, i.e., how much iron would be needed to overcome sediment phosphorus release.

Future research should expand upon the studies of historic droughts. The research should be done in a lake without uranium so that ^{14}C-dating can be used. In some lakes, the inferences from the diatom record could likely be confirmed by mineralogical analyses. The senior author has observed alternating layers of black sediments with red layers in a number of lakes in the interior of B.C. (Green, Mahoney, and Roche lakes). The black layers are forming under high water levels and presumably all contain pyrite. The red layers are hematite which could not form under the present anoxic hypolimnia and were likely formed when the lakes were much lower.

Insights from this diatom study should influence the management of Chain Lake. The extreme of increasing the lake depth to produce a deeper stable hypolimnion is not a simple option. Simple extrapolation of the diatom diversity data (Fig. 5) indicates an increase in water level of about 2 m would be required. Dredging 2 m of sediment to deepen the hypolimnion would be a very large and expensive project. Raising the lake 2 m would further flood a large swampy area at the head of the lake and the reflux of nutrients from the flooded swamp could override the effect of a deeper hypolimnion.

The other extreme of dropping the lake level to reduce stratification should reduce phytoplankton production and sediment phosphorus release. However, a lower water level would likely lead to more macrophyte growth. Also a smaller water volume would result in less oxygen storage for winter survival of trout.

Only one observation supports the perception of long-term residents that Chain Lake has become more eutrophic. About the time that the dam was raised in 1957, Asternionella formosa, an indicator of eutrophication (Brugam 1988), became common in the sediments (Murphy 1987). The study of the piston core indicates that water level changes can affect eutrophication and it is possible that raising the dam 1.2 m enhanced sediment phosphorus release. Moreover, the raising of the dam may have resulted in anoxic conditions in the sediments of the swamp, less iron complexation of phosphorus, enhanced phosphorus loading to the lake, and more algal growth.

Any management option that results in oxidized sediments should greatly reduce eutrophication of Chain Lake. Hypolimnetic withdrawal might be an effective treatment for Chain Lake. The water from the diversion should provide adequate flow to flush anoxic water, enhance phosphorus flushing from the lake and reduce sediment release of phosphorus.

The water diversion should be evaluated for more than its impact of eutrophication. The diversion would provide an adequate water supply for hydraulic dredging of sediments without a loss of lake level. Some dredging will be necessary to maintain the lake. The diversion would be useful to maintain water levels in a drought. Our diatom studies of about half of the piston core indicate that at least five dry periods have occurred. If the greenhouse effect produces a local drought, the water diversion will be required to maintain water levels.

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List of Figures

5) Diversity of Diatoms

6) Sedimentation Rate

7) Forms of Iron in Chain Lake Sediments

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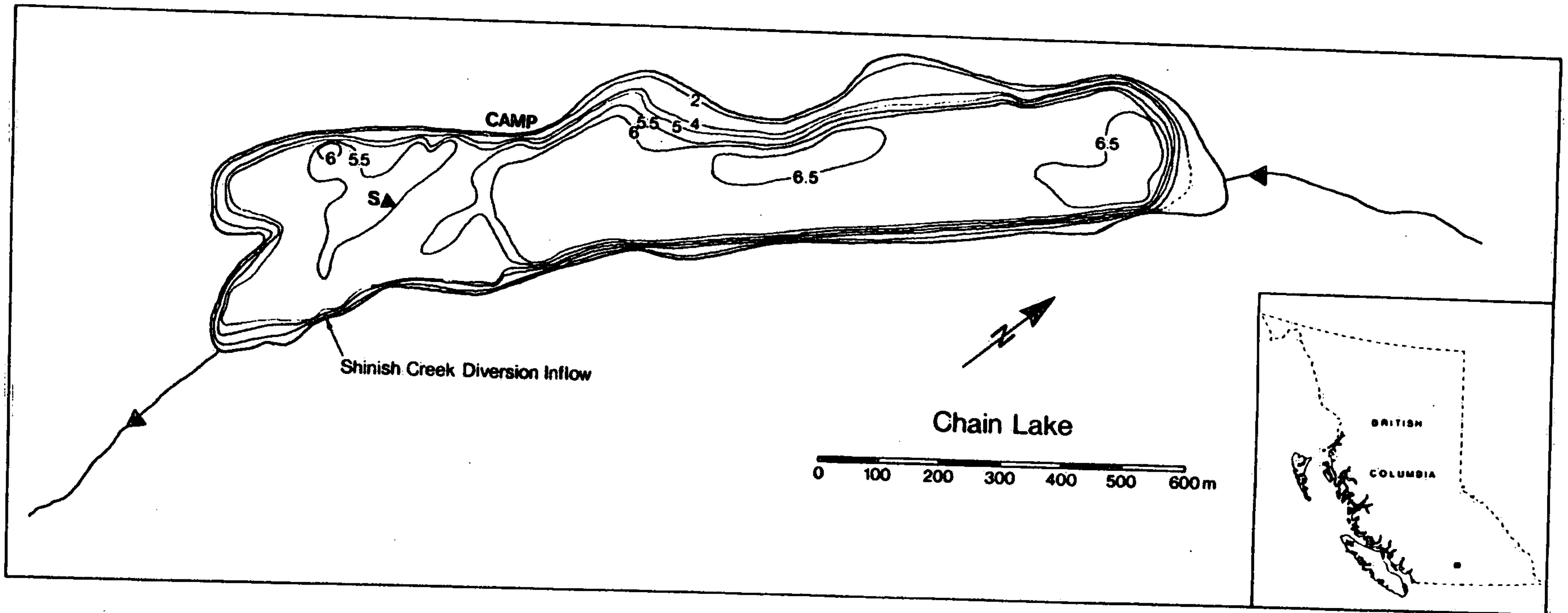


Figure 1 Chain Lake. Depth contours are in meters.

Figure 2a

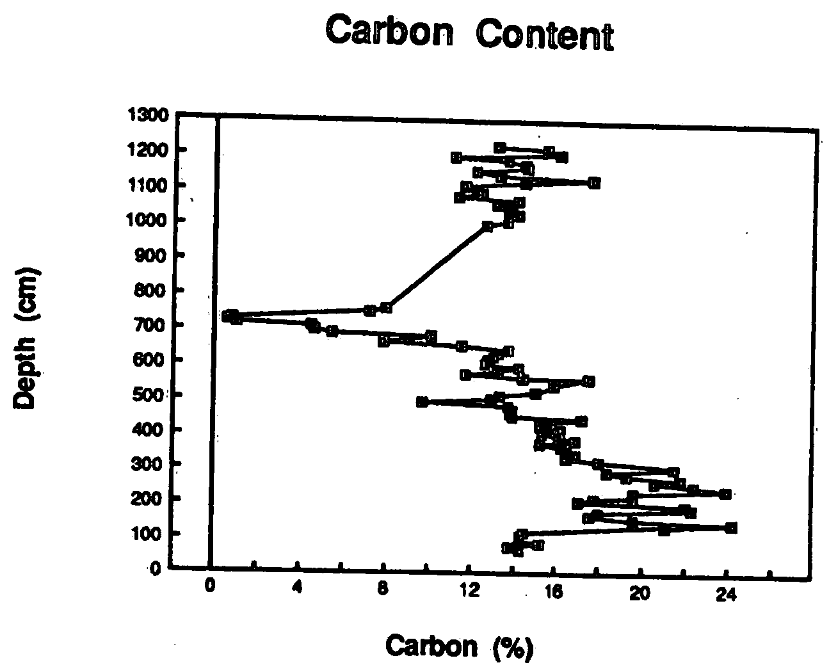


Figure 2b

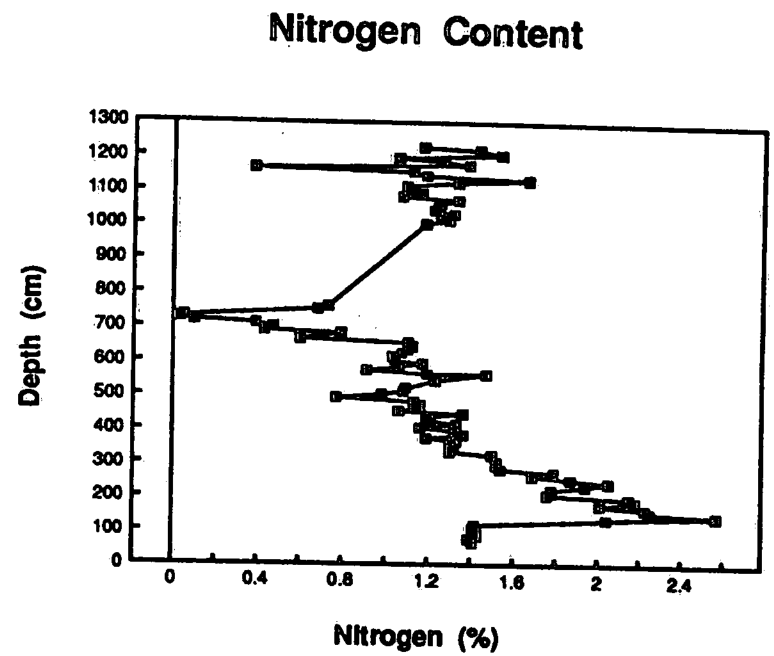


Figure 2c

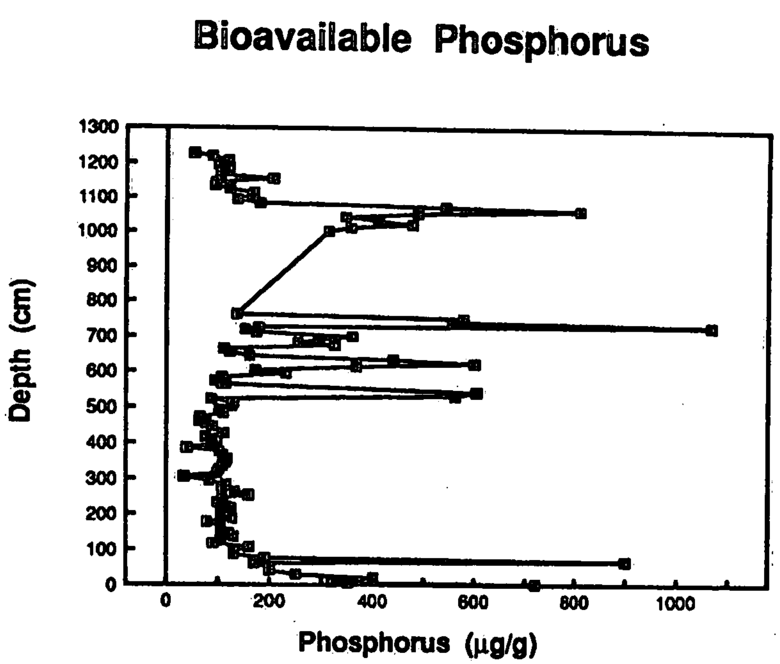


Figure 2d

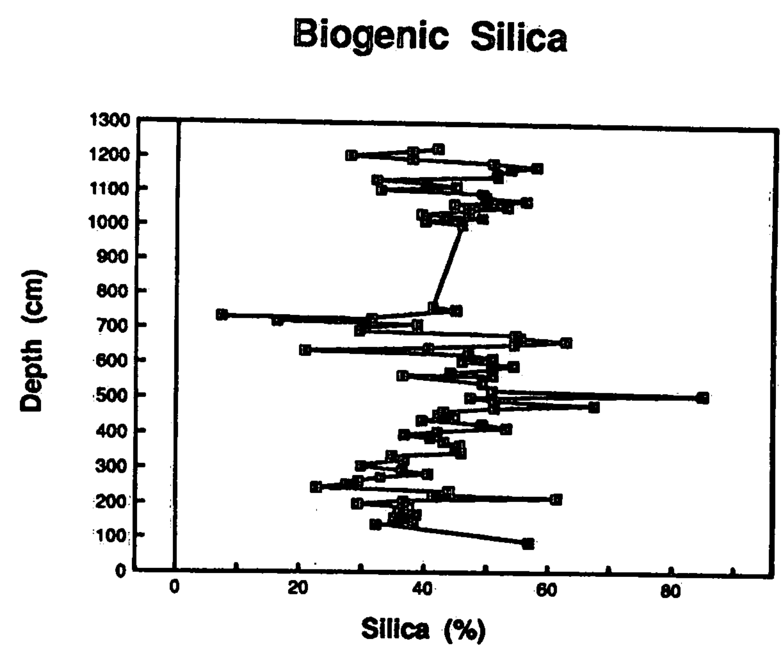


Figure 3

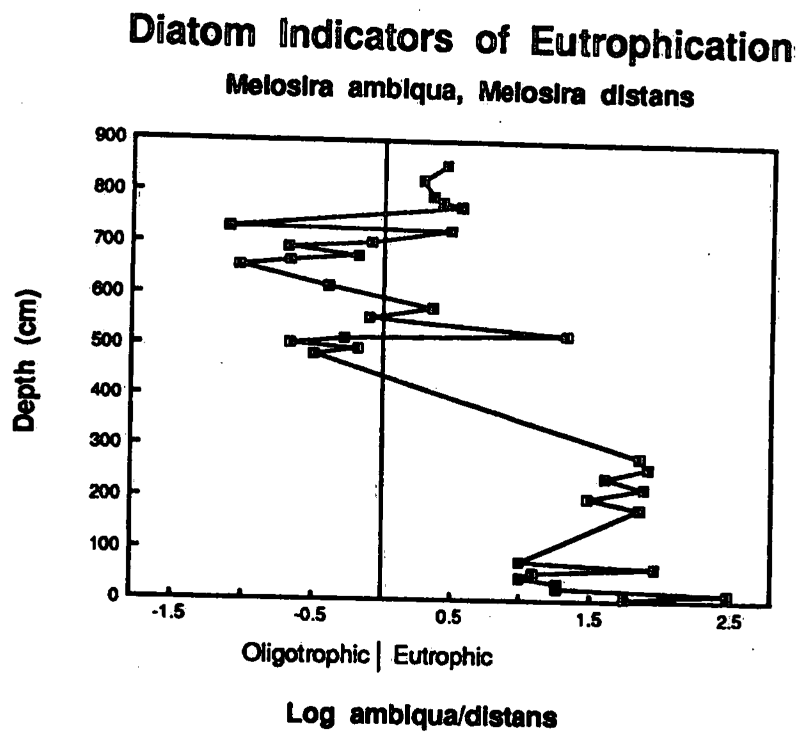


Figure 4

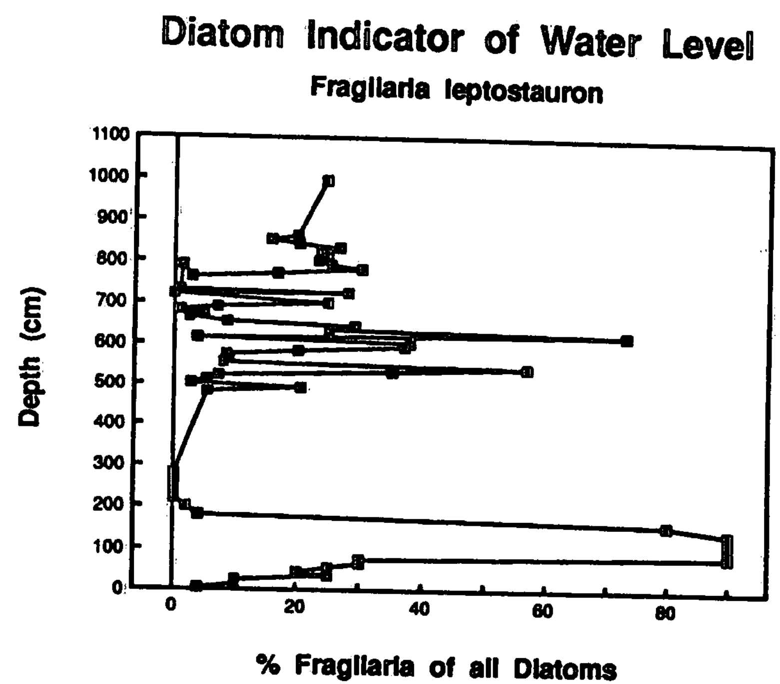


Figure 5

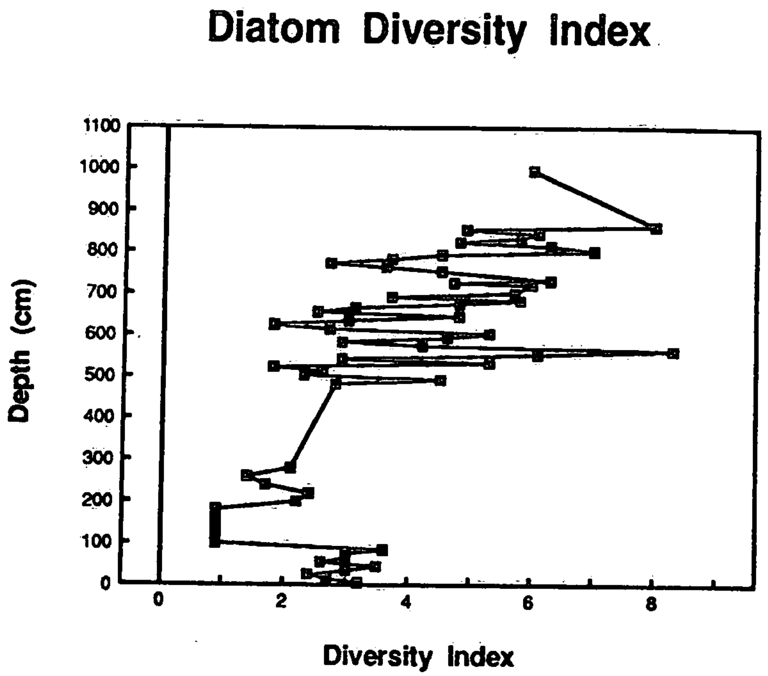

Diatom Diversity Index
Depth (cm)
1100
1000
900
800
700
600
500
400
300
200
100
0
0
2
4
6
8
Diversity Index

Figure 6

VARIATIONS IN SEDIMENTATION RATE

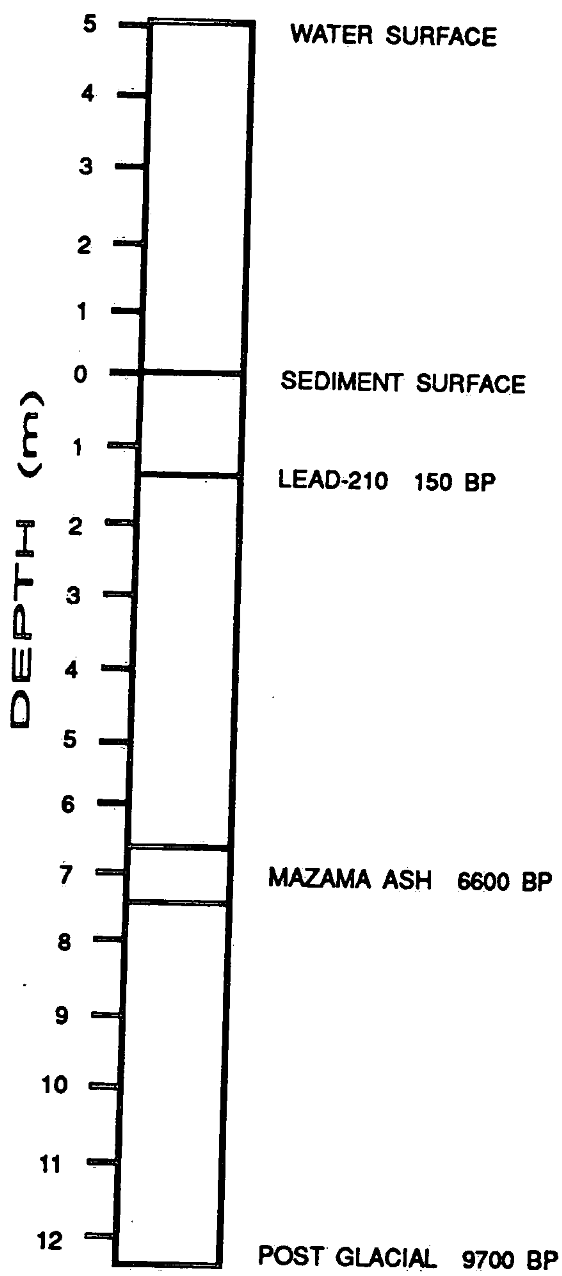
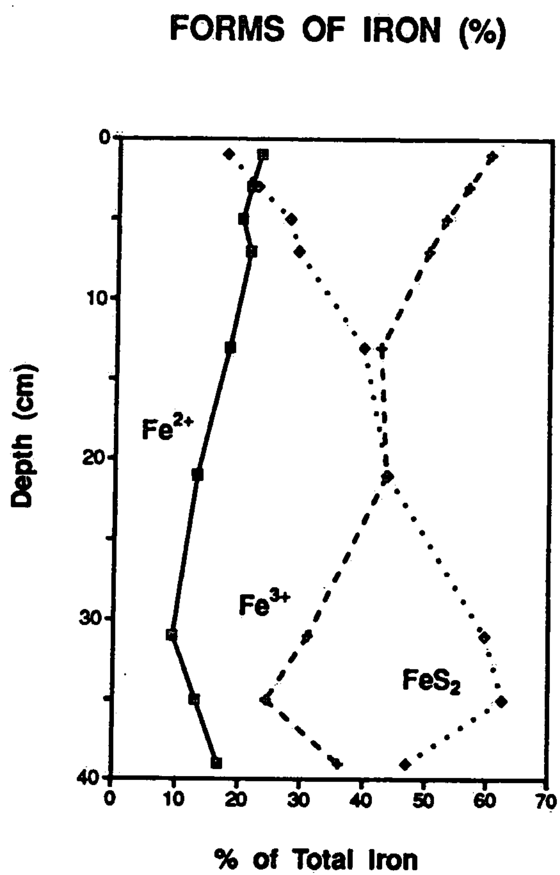


Figure 7



FORMS OF IRON (%)
Depth (cm)
0
10
20
30
40
Fe2+
Fe3+
FeS2
0
10
20
30
40
50
60
70
% of Total Iron

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Environment Canada Environnement Canada

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