THE PHYSICAL AND CHEMICAL DESCRIPTION OF THE LIMNETIC SEDIMENTS FROM LANGFORD LAKE, SOUTH VANCOUVER ISLAND, BRITISH COLUMBIA

by

Colin J.P. McKean
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to the required standard

[redacted]

E.M. Hagmeier

[redacted]

P.T. Gregory

[redacted]

F.P. Robinson

[redacted]

M.J.R. Clark

Supervisor: Dr. Edwin M. Hagmeier

ABSTRACT

Langford Lake was chosen to observe the effects of climate, geology, and geomorphology on the physical appearance and chemical composition of lake sediments. Thirty-two surface sediment samples, and two cores (8 and 12 m) were collected from the hypolimnion (> 7 m water depth) of Langford Lake. The results indicate that the analytical and within-site variability is sufficiently low that one sample or core per site is representative of that site.

The elements analysed from the surface sediments exhibited several different horizontal distributions. The concentrations of the elements associated with the organic fraction (C, Ca, and Kjeldahl nitrogen) decreased with increasing water depth. Longer settling times for seston with increasing water depth, and the redistribution of sediments during the process of sediment focusing, permits more complete decomposition of the organic fraction.

Fe and Mn concentrations also decreased with increasing water depth due to lower pH and redox potentials in the deeper waters. Al, and Mg concentrations appeared to be highest near the shores where the erosion of clastic materials would be highest. Phosphorus concentrations exhibits a similar distribution as the organic fraction. However, its horizontal distribution is more complicated because inorganic phosphorus can be bound in the sediments to the minerals of Fe, Al, and Mn.

The sediments of Langford Lake are primarily composed of autochthonous organics, inorganic diatom frustrules, and inorganic amprophous minerals, forming a homogeneous yellow-brown organic Limus detrituosus. Limus sediments dominated the surface sediments and most of the vertical stratigraphy. Based on physical appearance, the core stratigraphy could be divided into three organic layers, a layer of volcanic tephra from Mount Mazama, a zone of allochthonous clastics (clay) representing the influence of the Vashon glaciers, and a zone representing the interphase between the clastic and organic zones.

The chemical analysis of the core indicates that Al and Mg are primarily associated with the clastics minerals, because their concentrations are highest in the clay zone. The concentrations of Fe, Mn, and P are thought to be the result of the weathering and leaching of minerals from the drainage basin, because their concentrations are highest in the non-clastic (organic) sediments.

The organic C:TKN ratio of the core's organic fraction is approximately 10:1, indicating autochthonous organic production. The source of the carbon and nitrogen is the fixation of atmospheric carbon and nitrogen by plants and bacteria, repectively. In contrast, the source of inorganic elements is from the erosion and/or weathering of minerals from within the air- and watershed. The organic carbon content of the core sediments is positively correlated with phosphorus, indicating the weathering and leaching of phosphorus from the watershed limits the rate of autochthonous production and deposition (eutrophication) in Langford Lake.

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E.M. Hagmeier

[redacted]

P.T. Gregory

[redacted]

F.P. Robinson

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M.J.R. Clark

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I would like to dedicate my thesis to my father. His unquestioned dedication to his work and family provides an important role model and work ethic.

Finally, I would like to thank Shawn McKean for her assistence in preparing the thesis, her patience, and her support particularily during periods of frustration and low moral.

1. INTRODUCTION

The physical and chemical characteristics of a freshwater system are largely determined by the effects of climate on the geology and geomorphology of the drainage basin (Wetzel, 1982). These interactions determine rates of erosion and weathering of primary and secondary minerals, which in turn determines the amount and composition of dissolved and suspended materials contained within the basin runoff, and the water quality of the lake (ionic composition, nutrient loading and cycling, etc.; Mackereth, 1966; Lewis and Weibezahn, 1981; Pennington, 1981; Lindsay, 1979). The water quality of the lake in conjunction with the lake's morphology determines to a large degree the freshwater biocenosis (Rawson, 1956; Lund, 1965) and the rates of primary organic production within the system (Rawson, 1955; Ryder, 1965; Schindler, 1974; Vollenweider, 1968).

Sediments within the freshwater environment are a complex mixture of biogenic and abiogenic compounds that originated within the lake or watershed. The concentrations of the various sediment fractions are a function of the relative sedimentation rates of allochthonous and autochthonous organic and inorganic materials (Brunskill *et al*., 1971). Lake sediments are frequently used to study the processes within the watershed because they retain a relatively full record of the environmental conditions from which they were derived (Pennington, 1981).

Surface sediment samples and sediment cores have been used extensively to describe the trophic status of a lake (Birks and Birks, 1980; McKean, 1986), the watershed geology (Abernathy, 1984; Dean and Gorham, 1976; Cowgill and Hutchinson, 1970; Muller *et al*., 1972), basin development (Mackereth, 1966; Lewis and Weibezan, 1981), pollution (Charles, 1985; Nordin *et al*., 1985), and the biocenosis of a lake and its basin using diatoms, pollen, zooplankton, chironomids, and chrysophyceans (Birks and Birks, 1980; Smol, 1985).

Sediment studies in the Pacific Northwest of North America have focussed on pollen (Hansen, 1950; Heusser, 1960; Mathews, 1973; Tsukada *et al.*, 1981; Hebda, 1983; Zirul, 1967), diatoms (Abella, 1984; Brown, 1979; Brugam, unpubl.; Stockner, 1972; Stockner and Benson, 1967), and invertebrates (Tsukada *et al.*, 1981). To date, the physical description and chemical composition of limnic lake sediments from the Pacific Northwest has not been completed. The primary objectives of this research were to obtain the post-glacial (Holocene) sediment stratigraphy of a lake from the Pacific Northwest, and to relate the observed physical and chemical components of the sediment to the interactions of climate on the geology and geomorphology of the drainage basin.

Langford Lake, near Victoria, British Columbia, was chosen as the study site because there are several detailed publications on the water quality and history of this lake (Slaney, 1972; Brown, 1978; McKean and Munteanu, 1981; Nordin and McKean, 1987), and the Holocene plant communities and inferred climatic conditions have been determined for Vancouver Island (Zirl, 1967; Hebda, 1983).

2. DESCRIPTION OF STUDY AREA

2.1 LAKE AND WATERSHED MORPHOLOGY

Langford Lake is located on the southern end of Vancouver Island, 12 km west of Victoria, British Columbia (Figure 1; 48° 27' north and 123° 31' west). The pertinent morphological data for the lake are summarized in Table 1. The elevation and area of the lake are approximately 62 m and 60 hectares, while the drainage area is approximately 320 hectares (Figure 2). About 50 percent of the Langford Lake watershed drains areas with moderate relief. Skirt Mountain to the north has a maximum elevation of 340 m, while an unnamed knoll to the south-west has an elevation of 160 m. The remaining watershed is lowlying, of which the area to the south and south-east are subject to flooding during the winter. The areas immediately to the north and east of the lake have been developed with residential housing (Figure 2).

There are a few ephemeral streams located around the lake. The major inflow drains the area south of the Esquimalt and Nanaimo Railway (Figure 2). Runoff is channelled from this area to the lake through a culvert near the south-east shore of the lake. The drainage from the north is intercepted by two major roads and directed to the lake through a series of culverts and ditches.

The present day bathymetry of Langford Lake was delineated in 1954 by the Fish and Wildlife Branch of the Ministry of Environment (Figure 3). The maximum depth of 15.5 m is located at the east end of the lake, while the west end is considerably more shallow. Since Langford Lake is a 'kettle lake', the shape and depth of the lake is a reflection of the orginal shape and size of the ice block that formed the lake (Hutchinson, 1957). The mean depth and lake volume at the time of the bathymetric survey were 6.4 m and 3,843,000 m^3 (Balkwill, 1986).

Figure 1: Location of Langford Lake, South Vancouver Island

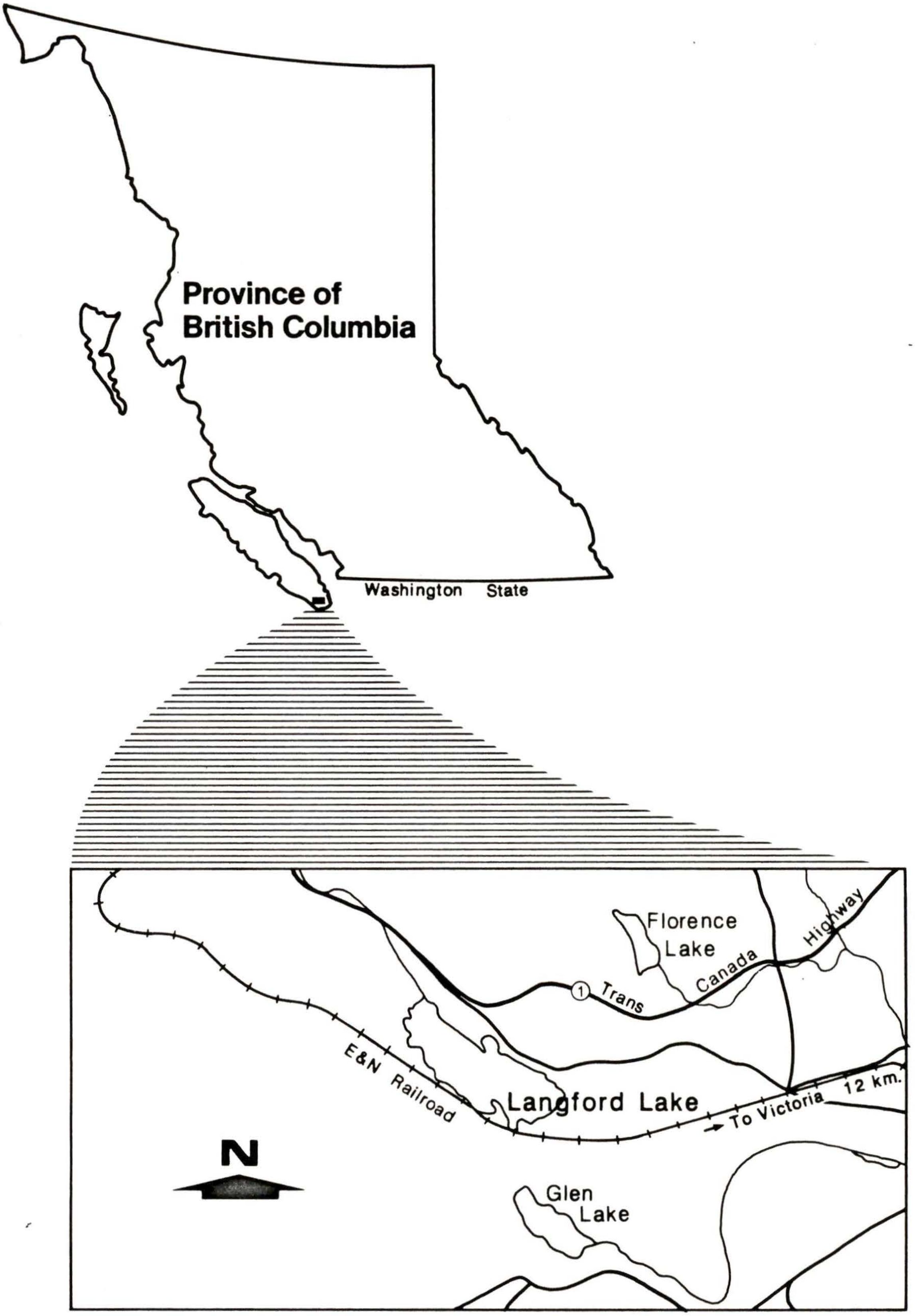

Province of British Columbia
Washington State
Florence Lake
1
Trans Canada Highway
E&N Railroad
Langford Lake
To Victoria 12 km.
Glen Lake
N

Figure 2: Topography, Inflow Streams, and Boundary of the Langford Lake Watershed

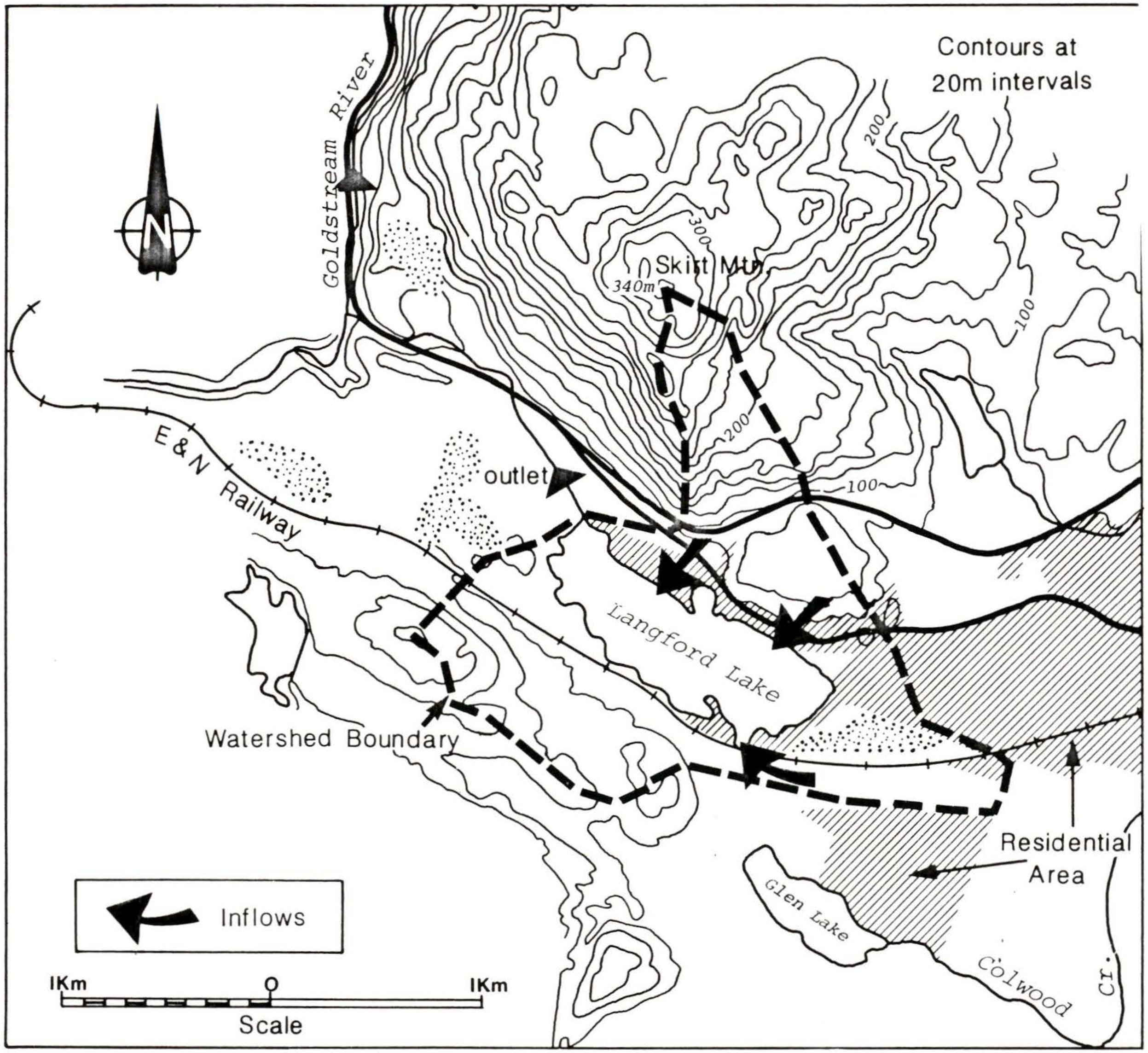

Contours at 20m intervals
Goldstream River
Skist Mtn.
340m
300
200
100
outlet
E&N Railway
Langford Lake
Watershed Boundary
Residential Area
Glen Lake
Colwood Cr.
N
Inflows
1Km
0
1Km
Scale

Figure 3: Bathymetry of Langford Lake
(from Balkwill, 1986)

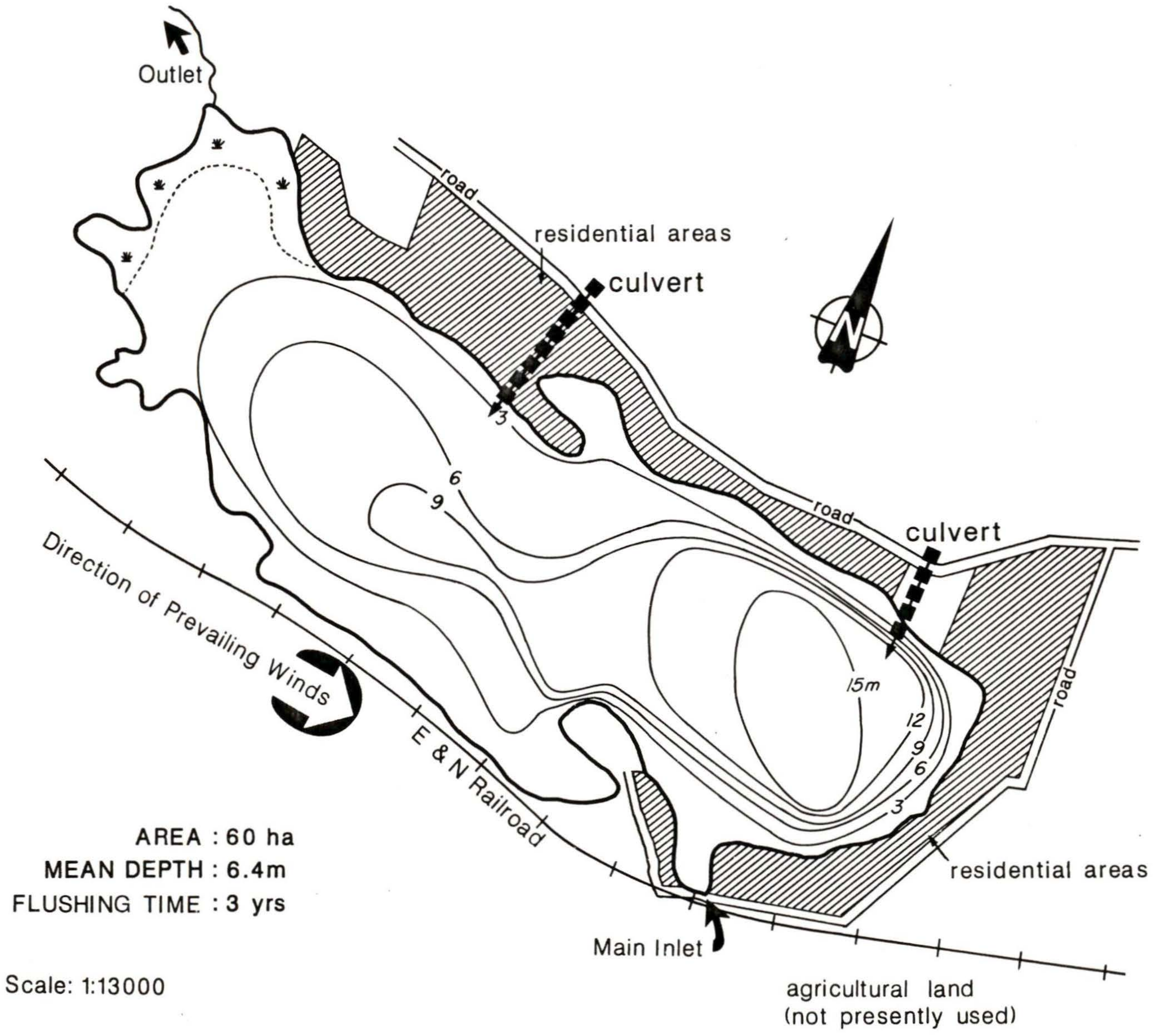

Outlet
road
residential areas
culvert
3
6
9
road
culvert
15m
12
9
6
3
road
residential areas
Direction of Prevailing Winds
E & N Railroad
Main Inlet
agricultural land
(not presently used)
AREA : 60 ha
MEAN DEPTH : 6.4m
FLUSHING TIME : 3 yrs
Scale: 1:13000

TABLE 1
Morphological Characteristics of Langford Lake and Its Watershed (from McKean and Munteanu, 1981)

Latitude	48° 27'
Longitude	123° 31'
Elevation (m)	62
Watershed size (ha)	320
Lake size (ha)	60
Lake volume (m^3)	3,843,000
Mean depth (m)	6.4
Maximum depth (m)	15.5
Flushing rate (yr^{-1})	0.3

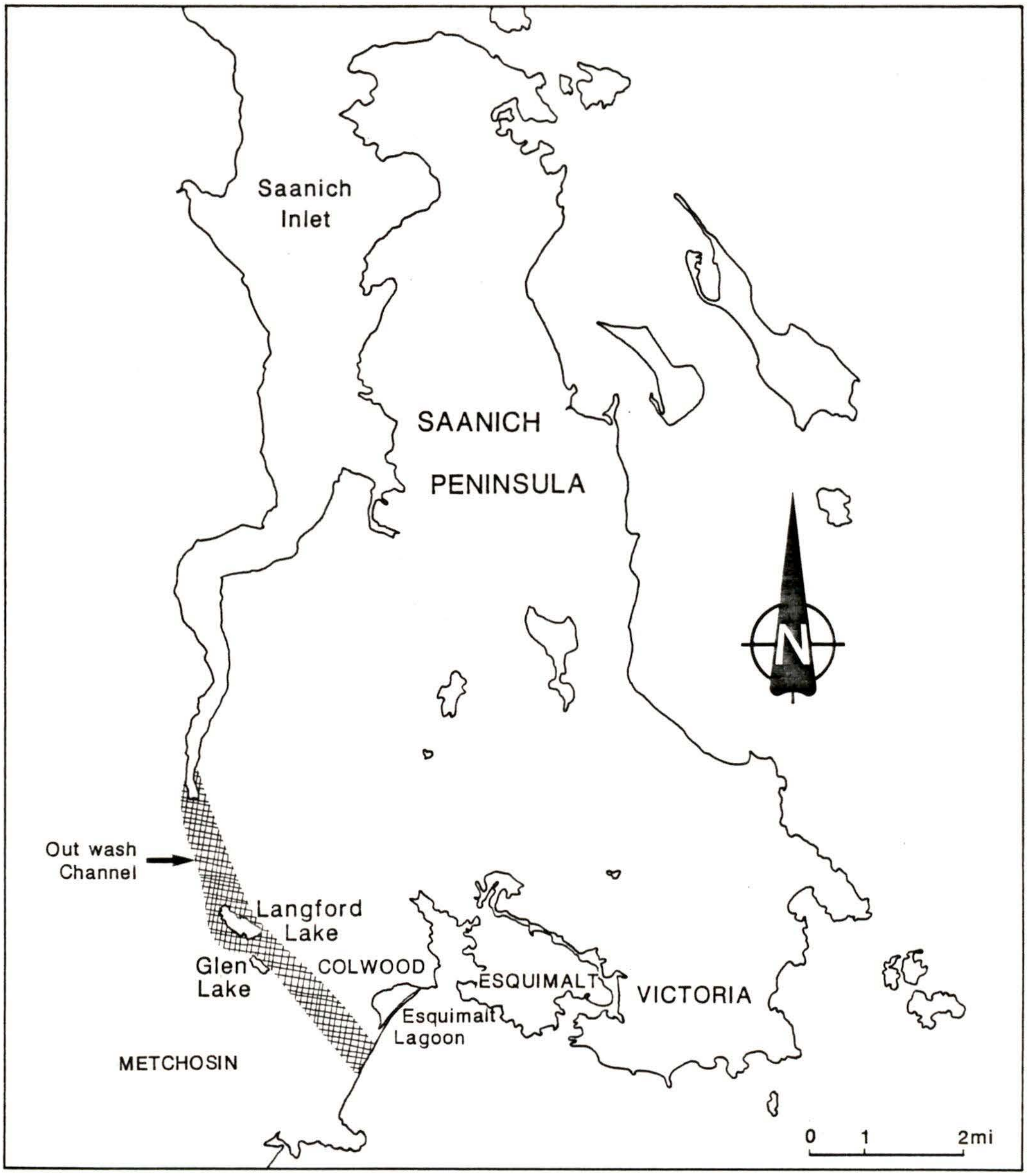
The flushing rate of Langford Lake is estimated using the runoff coefficients (mm of runoff/m^2) from Colquitz Creek (a similar basin 8 km east). The average runoff for Colquitz Creek is 350 mm/m^2 (Water Survey of Canada, 1981). By multiplying the runoff coefficient by the watershed size of Langford Lake, an estimated water input of 1,120,000 m^3 would be expected in an average precipitation year. A flushing time of 3 years is calculated using the Colquitz runoff coefficient (McKean and Munteanu, 1981).

2.2 LAKE FORMATION/WATERSHED DEVELOPMENT

Langford Lake was formed during the Vashon Stade, the period of maximum ice advance during the Late Wisconsin or Fraser Glaciation (Alley, 1974). The Fraser Glaciation (25,000 - 12,000 BP) was the last major glaciation in British Columbia, during which ice covered most of the province. In the Puget Sound and Strait of Georgia regions, the Fraser Glaciation is subdivided into several lower order geologic-climate units including the Evans Creek Stade, Vashon Stade, Everson Interstade, and the Sumas Stade (Armstrong *et al*., 1965). The ice advance of the Vashon Stade extended south into Puget Sound and east through the Straits of Juan de Fuca (Alley and Chapman, 1979). During the Vashon recession (14,000 - 13,000 BP) the Strait of Juan de Fuca was open while Saanich Inlet, located to the north of Langford Lake (Figure 4), was blocked with ice. The melt water from the local glaciers flowed south to the Strait, and formed an outwash plain of sand and gravel extending south through the present day location of Langford Lake toward Esquimalt Lagoon. Langford Lake was formed in the melt water channel by a large block of ice that had become separated from the main glacier. The build up of outwash materials around the ice, and the eventual melting of the ice, produced the depression which forms the lake today. This type of lake formation is termed 'Kettle Formation' (Hutchinson, 1957).

The present day landscape of the Langford Lake watershed is

Figure 4: Langford Lake in Relation to the Colwood Sands and Gravels


Saanich Inlet
SAANICH PENINSULA
N
Out wash Channel
Langford Lake
Glen Lake
COLWOOD
ESQUIMALT
VICTORIA
Esquimalt Lagoon
METCHOSIN
0
1
2mi

exposed bedrock with thin dystric brunisol soils on the slopes of Skirt Mountain and the knoll to the south-west (Farley, 1979), and thick fluvial deposits in the lowlying areas (Slaney, 1972). The original outflow from the lake flowed to the south-east (the present day inflow, Figure 2) toward Esquimalt Lagoon through an extensive marsh area. Presumably the marsh areas at the outlet were contiguous with the lake.

Between 1884 and 1886, the Esquimalt and Nanaimo (E&N) Railway was built along the lake's southern shore (Slaney, 1972). The construction of the railway diverted runoff from the southern watershed to the marshy area at the outlet. A railway trestle was required to cross the marshy outlet. The original trestle was replaced (year unknown) with a culverted embankment (Slaney, 1972).

Flooding of lowlying areas during periods of high precipitation became an issue as residential development increased. In 1932, the Department of Public Works dug an alternate outflow at the north-west end of the lake (Figure 2) to reduce the incidence of flooding (Priestman, 1963). The new outflow reduced the lake's elevation and volume. Now the old outflow flows into the lake, draining the area south of the railway (Figure 2).

Residential development in the lake's watershed was sparse before 1940, mainly limited to summer cottages along the north and east lakeshore (Figure 3). Fifty-seven permanent dwellings were recorded in 1958 by Handley (1972). Residential housing increased to 100 in 1972 (Slaney, 1972), and 160 in 1980 (McKean and Munteanu, 1981).

Agricultural development has been restricted to the lowlying marshy area that formed the orginal outlet before the alternate outflow was constructed. The area has not been cultivated in recent years.

2.3 GEOLOGY

The geology of the Langford Lake watershed has three important features: the Wark Gneiss to the north, the Leech River Formation to the south, and the Colwood Sands and Gravels immediately around the lake (Figure 5). The specific geology and chemistry of the bedrock can only be generalized (Huang, 1962; Geological Survey of Canada, 1981), because no geological studies have been completed within the watershed (Whilton, pers. comm.).

The Wark Gneiss to the north is a diorite, gabbro, and amphibolite deposit formed during the Paleozoic era (230-570 million years BP). The chemical composition of the average diorite, gabbro, and amphibolite is summarized in Table 2. Silica oxides are the most common mineral in the Gneiss, composing about 50% of the bedrock by weight. Aluminum, iron, and calcium are the next most common minerals at approximately 15, 10, and 9%, respectively.

The Leech River Formation is distinct from the Wark Gneiss in that it is contemporaneous with the Olympic Mountains to the south, across the Strait of Juan de Fuca (Whilton, pers. comm.). The rock is mostly metamorphosed siliceous sedimentary rock (chert and argillite), with some volcanic intrusion (rhyolite, schist (chlorite), and basalt) (Geological Survey of Canada, 1981). The chemical composition of the Leech River Formation is summarized in Table 2. The silica oxide content is higher than the Wark Gneiss; however, the calcium, magnesium, and aluminum are lower. The iron content is similar in most rock formations except it is lower in the chert deposits.

2.4 CLIMATE

The climate of southern Vancouver Island is influenced by the mountains to the west and south, and the surrounding waters of the Straits of Georgia and Juan de Fuca. During the summer, westerly winds

Figure 5: Geology of the Langford Lake Watershed
(Geological Survey of Canada, 1981)

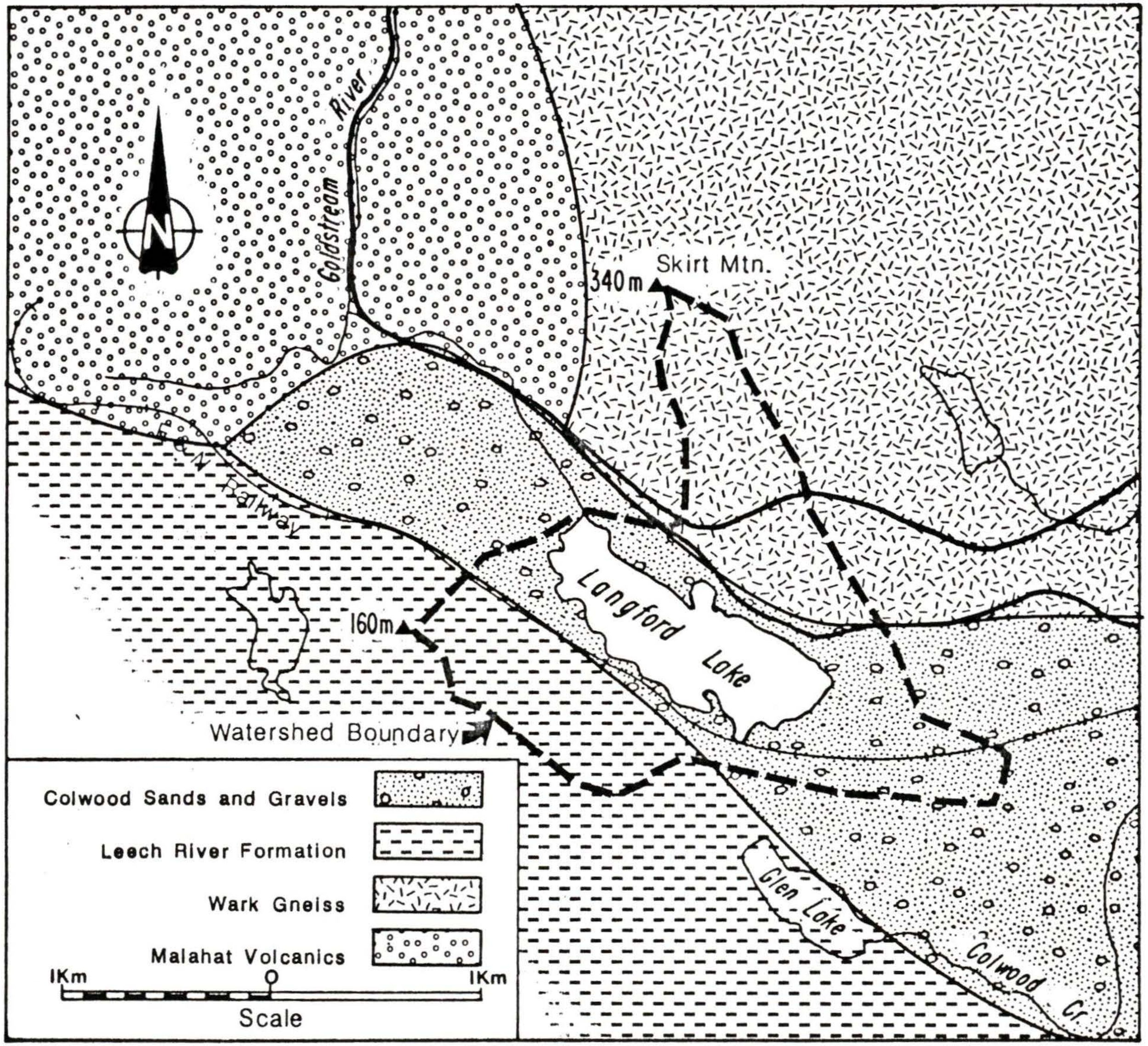

N
Goldstream River
E&N Railway
340m
Skirt Mtn.
Langford Lake
160m
Watershed Boundary
Glen Lake
Colwood Cr.
Colwood Sands and Gravels
Leech River Formation
Wark Gneiss
Malahat Volcanics
1Km
0
1Km
Scale

Table 2.
General Chemical Composition of the Bedrock Geology Within the Langford Lake Watershed.

Mineral	WARK GNEISS			LEECH RIVER FORMATION				Average of Cols. 1 to 7 (%)	Elemental* Concentration	
	Diorite (%)	Gabbro (%)	Amphibolite	Chert (%)	Argillite	Rhyolite (%)	Chlorite Schist			(mg/g)
SiO_2	51.9	50.8	50.3	82.7	60.8	73.7	50.3	60.0	Si	350
TiO_2	1.5	2.0	1.6	---	0.6	0.2	1.6	1.3	Ti	7.8
Al_2O_3	16.4	14.0	15.7	1.8	16.7	13.5	15.7	13.4	Al	71
Fe_2O_3	2.7	2.9	3.6	1.0	1.4	1.3	3.6	2.4	Fe	16.7
FeO	7.0	9.1	7.8	0.3	5.8	0.8	7.8	5.5	Fe	43
MnO	0.2	0.2	0.2	0.1	0.1	0.1	0.2	0.1	Mn	1.0
MgO	6.1	6.3	7.0	1.1	3.8	0.3	7.0	4.5	Mg	27
CaO	8.4	10.4	9.5	2.9	0.8	1.1	9.5	6.1	Ca	43
Na_2O	3.4	2.2	2.9	0.5	4.3	3.0	2.9	2.7	Na	20
K_2O	1.3	0.8	1.1	2.6	2.1	5.4	1.1	2.1	K	16.8
P_2O_5	0.4	0.2	0.3	0.2	---	0.1	0.3	0.3	P	1.0

* Using the atomic weights of the minerals and the individual elements, the minerals were converted to a concentration (mg/g) and averaged.

from Huang (1962).

through the Strait of Juan de Fuca moderate maximum daily temperatures. The mean July daily temperature from the Victoria Tillicum weather station (5 km east) is 16.8°C (Environment Canada, 1980). Sufficient radiant heat is available in the late spring and summer to stratify the lake thermally from May through October (McKean and Munteanu, 1981).

During the winter, the prevailing south-easterly flow brings mild wet weather from the Pacific Ocean. The majority of the moisture is deposited on the western-facing slopes of the Vancouver Island Mountains, forming a rainshadow on the east coast of Vancouver Island. The Olympic Mountains to the south also create a rainshadow on southern Vancouver Island. The net effect of the Pacific Ocean and the mountains is a mild winter climate with moderate precipitation. The mean January daily temperature from the Victoria Tillicum weather station is 3.7°C (Environment Canada, 1980). The result is that ice formation on Langford Lake and winter stratification are rare; consequently, the lake is considered monomictic (Hutchinson, 1957).

From a hydrologic perspective, the mild climatic conditions in the winter do not permit the development of a snow pack. As a result, the majority of runoff occurs during the winter months - the period of heaviest precipitation. This differs from the pattern of most Canadian watersheds, which have peak runoff during the May - July period, due to snow-melt. The 30 year annual precipitation records from the Victoria Highland (152 m elevation) and Tillicum (23 m elevation) weather stations are 1156 and 836 mm respectively (Water Survey of Canada, 1981).

2.5 WATER CHEMISTRY

Water chemistry from Langford Lake was examined in 1980, 1983, 1984, and 1985 by the Water Management Branch of the British Columbia Ministry of Environment and Parks (McKean and Munteanu, 1981; Nordin and McKean, 1987.). A summary of the general water chemistry and related parameters is presented in Table 3. The principal cations are calcium (18.8 mg/L), sodium (6.4 mg/L), magnesium (3.8 mg/L), and potassium (0.6 mg/L). The principal anions are bicarbonate (68 mg/L), chloride (10 mg/L), and sulphate (5.9 mg/L). Langford Lake, and other lowland lakes on eastern Vancouver Island, typically have moderate water hardness ranging from 50-100 mg/L. Lakes from higher altitudes or from the west coast have softer water because of higher rainfall (McKean, unpubl.).

An anion-cation balance calculated using the procedures outlined by Riehl (1970) showed that calcium and bicarbonate are the most common dissolved inorganic constituents in Langford Lake. The concentrations of sodium and chloride are higher than in most other lakes in British Columbia (Warrington, unpubl.) because the deposition of Na and Cl is elevated near the oceans (Mackereth, 1966).

The primary productivity and algal standing crop in Langford Lake during the summer months are governed by the availability of phosphorus (McKean and Munteanu, 1981). Spring overturn phosphorus concentrations averaged 25 µg/L between 1980 and 1986 (Nordin and McKean, 1987). Langford Lake is considered to be eutrophic because of the high concentrations of phosphorus and the concomitant algal growth and poor water transparency (Wetzel, 1983; Nordin, 1985). The major sources of phosphorus are from the lowlying area to the south-east that was originally the lake's outlet, and internal phosphorus loading (McKean and Munteanu, 1981). Internal phosphorus loading refers to the process where by the phosphorus is released from hypolimnetic sediments. Internal loading in the hypolimnion of Langford Lake occurs under reducing conditions (McKean, 1986).

2.6 LAKE BIOLOGY

The dominant phytoplankton in Langford Lake varies seasonally, with diatoms predominating in the winter (*Asterionella formosa*,

TABLE 3
Summary of the Pre-aeation Water Chemistry from Langford Lake (from McKean and Munteanu, 1981)

Parameter	Epilimnion mean±s.d. (n)	Hypolimnion mean±s.d. (n)
General Ions & related tests		
Alkalinity, total (mg/L)	55.7± 1.3 (13)	63.4 ± 6.3 (7)
Calcium, total (mg/L)	18.8 ± 0.9 (16)	20.5 ± 1.0 (9)
Carbon, bicarbonate (mg/L)	68.3 ± 12.4 (15)	69.0 ± 10.1 (8)
Chloride, dissolved (mg/L)	10.0 (1)	10.4 (1)
Hardness, total (mg/L)	57.2 ± 9.1 (8)	61.7 ± 8.3 (5)
Magnesium, total (mg/L)	3.8 ± 0.1 (15)	4.0 ± 0.1 (6)
pH	8.5 ± 0.6 (16)	7.4 ± 0.2 (9)
Potassium, dissolved (mg/L)	0.6 (1)	0.6 (1)
Residue, total diss. (mg/g)	92.5 ± 4.7 (16)	100.3 ± 6.2 (8)
Silica, reactive (mg/L)	0.9 ± 0.8 (16)	2.5 ± 1.4 (8)
Sodium, dissolved (mg/L)	6.4 (1)	6.5 (1)
Sulphate, dissolved (mg/L)	5.9 ± 0.6 (5)	5.8 ± 0.2 (1)
Nutrients		
Carbon, organic (mg/L)	5.2 ± 1.6 (16)	4.7 ± 1.9 (9)
Nitrogen, Kjeldahl (mg/L)	0.5 ± 0.1 (16)	0.5 ± 0.2 (8)
Phosphorus, total (mg/L)	0.025± 0.015 (16)	0.098± 0.150 (9)
Water Clarity		
Colour, true (TCU)	5.0 ± 0.0 (7)	6.7 ± 2.6 (6)
Turbidity (NTU)	1.9 ± 1.3 (8)	1.9 ± 1.3 (9)
Transparency, Secchi (m)	3.5 ± 1.0 (12)	

Fragilaria crotonensis, *Stephanodiscus niagare*, *Melosira* spp., *Synedra* spp.) and cyanobacteria in the summer (*Anabaena* spp., *Aphanizomenon flos-aquae*, and *Microcystis* spp.). The above diatoms and cyanobacteria are typical of eutrophic conditions (Rawson, 1956; Huchinson, 1967). The appearance of *A. flos-aquae* and *Anabaena* spp. early in the summer and the succession to a *Microcystis* community follows the common cyanobacteria successional pattern of eutrophic lakes (Wetzel, 1975). The cyanobacteria are sensitive to low light and temperatures, particularly following destratification or fall overturn when mixing of the lake increases. Mixing at fall overturn replenishes the supply of dissolved silica oxide in the photic zone. The increased silicon supply combined with the mixing and low light conditions during the winter favors the presence of the eutrophic diatoms listed above.

Zooplankton populations in Langford Lake are dominated by rotifers (e.g. *Branchionus* spp.). The copepods *Cyclops haueri*, *Diaptomus* spp. are also common. The absence of large cladocerans such as *Daphnia* spp. is typical of eutrophic lakes with an anoxic hypolimnion and planktivorous fish (Jones, 1986; Shapiro, pers. comm.).

Langford Lake supports a few species of fish including the pumpkin-seed (*Lepomis gibbosus*), small mouth bass (*Micropterus dolomieu*), catfish (*Ictalurus nebulosus*), and a stocked population of rainbow trout (*Salmo gairdneri*). The success of the centrarchid fish (pumpkin-seed and small mouth bass) is a reflection of the eutrophic conditions of the lake (Griffith, pers. comm.).

A destratification aeration system was installed in 1984 at the deepest point of the lake (Figure 3), using capital funds from the Habitat Conservation Fund (Hay, pers. comm.). The objective of the aeration system was to reduce the effects of eutrophication by eliminating internal phosphorus loading, improving water transparency, reducing cyanobacteria and algal biomass, and increasing habitat for rainbow trout through the oxygenation of the hypolimnion.

Since 1985, the aeration system has effectively eliminated the thermal stratification of the lake, oxygenated the zone of the lake that formed the hypolimnion, lowered spring overturn phosphorus concentrations, and shifted the phytoplankton community from cyanobacteria to diatoms (Nordin and McKean, 1987).

2.7 PRESENT TERRESTRIAL PLANT COMMUNITY

The plant community of the Langford Lake watershed is best described using the biogeoclimatic system developed by Krajina (1969) for the Province of British Columbia. Table 4 outlines the biogeoclimatic zones that occur on Vancouver Island. The majority of Vancouver Island is within the Mesothermal Formation (Coastal Douglas Fir and Coastal Western Hemlock Biogeoclimatic Zones), while the higher elevations are within the Microthermal Coniferous Forest Formation (Mountain Hemlock Biogeoclimatic Zone).

The Pacific Coastal Mesothermal Forest (PCMF) is the only biogeoclimatic region within the Mesothermal Formation. The Region is typified by mild winters, dry summers, and moderate annual precipitation. The Coastal Douglas Fir (CDF) and Coastal Western Hemlock (CWH) are the biogeoclimatic zones within the PCMF Region.

The Coastal Western Hemlock Biogeoclimatic Zone (CWH) is the wetter of the two biogeoclimatic zones, and usually has mild winters and cool summers. The CWH is subdivided into two subzones corresponding to differences in precipitation. The drier coastal Western Hemlock subzone (CWHa) is characterized by an annual precipitation of 165-280 cm, and by the following coniferous species: *Pseudotsuga menziesii*, *Tsuga heterophylla*, *Thuja plicata*, *Abies grandis*, *Picea sitchensis*, *Pinus monticola*, *P. contorta*, and *Arbutus menziesii* (the latter in the drier areas only). The wetter coastal Western Hemlock subzone (CWHb), is characterized by a rainy climate with an annual precipitation of 280-665 cm, and by the same

TABLE 4
Biogeoclimatic Units on Vancouver Island
(modified from Krajina, 1969)

Formation	Region	Zone		Subzone	
Apline	Alpine	Alpine Tundra	annual precipitation variable 70-280 cm	ATa	heavy cover and longer duration of snow, very short vegetative season, water easily available.
				ATb	lighter cover and shorter duration of snow longer vegetative season, water shortage may take place.
Microthermal Coniferous Forest	Pacific Coastal Subalpine Forest	Mountain Hemlock	microthermal subalpine with heavy snow cover over unfrozen ground; winter not severe, annual precipitation: 178-432 cm	MHa	lower elevations of the zone, shorter duration of snow, longer vegetative season forest stands.
				MHb	higher elevations of the zone, longer duration of snow, shorter vegetative season, forest parkland.
Mesothermal	Pacific Coast Mesothermal Forest	Coastal Douglas Fir	mesothermal marine subhumid with dry summer, annual precipitation: 66-152 cm.	CDFa	annual total precipitation: 66-102 cm.
				CDFb	annual total precipitation: 102-152 cm.
		Coastal Western Hemlock	mesothermal marine humid to rainy; annual precipitation 165-665 cm.	CWHa	annual total precipitation; 165-280 cm.
				CWHb	annual total precipitation; 280-655 cm.

coniferous trees as the CWHa subzone with the subsitution of *Abies amabilis* for *A. grandis*, and the addition of *Chamaecyparis nootkaensis* and *Tsuga mertensiana*.

The Coastal Douglas Fir (CDF) Biogeoclimatic Zone is drier than the CWH zone, and is also divided into two subzones corresponding to differences in precipitation. The drier subzone (CDFa) is characterized by Garry oak (*Quercus garryana*) and coastal Douglas fir (*Pseudotsuga menziesii*), and annual precipitation between 66 - 102 cm. The following trees are found in this zone: *Pseudotsuga menziesii*, *Abies grandis*, *Thuja plicata*, *Quercus garryana*, *Arbutus menziesii*, *Pinus contorta*, *Picea sitchensis* (rare), *Prunus emarginata*, *Alnus rubra*, *Acer macrophyllum*, *A. circinatum* and *Populus balsamifera* spp. *trichocarpa* are also frequent.

The wetter subzone (CDFb) is characterized by arbutus and coastal Douglas fir, and mean annual precipitation of 102 - 152 cm. The same species are present in this subzone as in the dry subzone, with the addition of *Picea sitchensis* and *Pinus monticola* and the significant absence of Garry oak.

The lower elevations of the Langford Lake watershed are clearly within the dry Coastal Douglas Fir subzone (CDFa). The higher elevations may have sufficient rainfall to be in the wetter subzone (CDFb).

2.8 HOLOCENE CLIMATE AND TERRESTRIAL PLANT COMMUNITIES

The climate and plant communities of North America and Europe have changed significantly since the last glaciation. Wright (1976) determined that the Holocene had three distinct climatic periods: a moist-cool period immediately after deglaciation, a warm-dry interval, and a return to cool moist conditions. The warm-dry interval was originally called the 'Hypsithermal', and was originally described as a time-parallel unit (Wright, 1976). The time-parallel phase implies changes in climate were immediately reflected by changes in tree species. Changes in precipitation and temperature are important factors determining plant communities, but forest communities may change slowly due to differential migration rates, and in some cases they have been influenced by Neolithic man. The result can be that climax forest communities lag significantly behind climatic changes. Wright (1976) proposes a change in the nomenclature of the warm-dry interval to the 'early Holocene xerothermic interval', described as a time-transgressive geographic interval that reflects regional time lags.

The Holocene plant communities of southern Vancouver Island have been assessed from the pollen records collected from two bogs. Heusser (1960) collected pollen from an unnamed bog on the Malahat (5 km west of Langford Lake), and Zirul (1967) collected pollen from Rithets Bog (5 km east). A third pollen study on northern Vancouver Island provides a complete climatic history for the last 14,000 years (Hebda, 1983). A summary of the three studies is illustrated in Figure 6. Of the above pollen studies, only Hebda (1983) did ^{14}C analysis, so that comparison of pollen horizons with other studies in the Pacific Northwest is difficult. Figure 7 summarizes the major shifts in pollen on Vancouver Island and qualitatively plots temperature and rainfall relative to present day conditions.

The late-glacial pollen zone at the Malahat bog was dominated by lodgepole pine (Pinus contorta) and alder (Alnus; Heusser, 1960). Rithet's bog does not contain a pine-alder pollen zone as the area was inundated by the marine environment during this period (Zirul, 1967). A lodgepole pine-alder zone extended from 14,000 - 11,500 BP at Bear Cove on northern Vancouver Island (Hebda, 1983), but persisted to about 10,500 BP in the Fraser Lowland (Mathews, 1973). The dominance of lodgepole pine was partly a result of soil immaturity, disturbed substrates, and a cool climate that was drier than today (Hebda, 1983). Support for the dry climate hypothesis is given by the dominance of lodgepole pine, and the absence of other conifers (particularly Sitka

Figure 6: Holocene Pollen Records for Vancouver Island
(modified from Hebda, 1983)

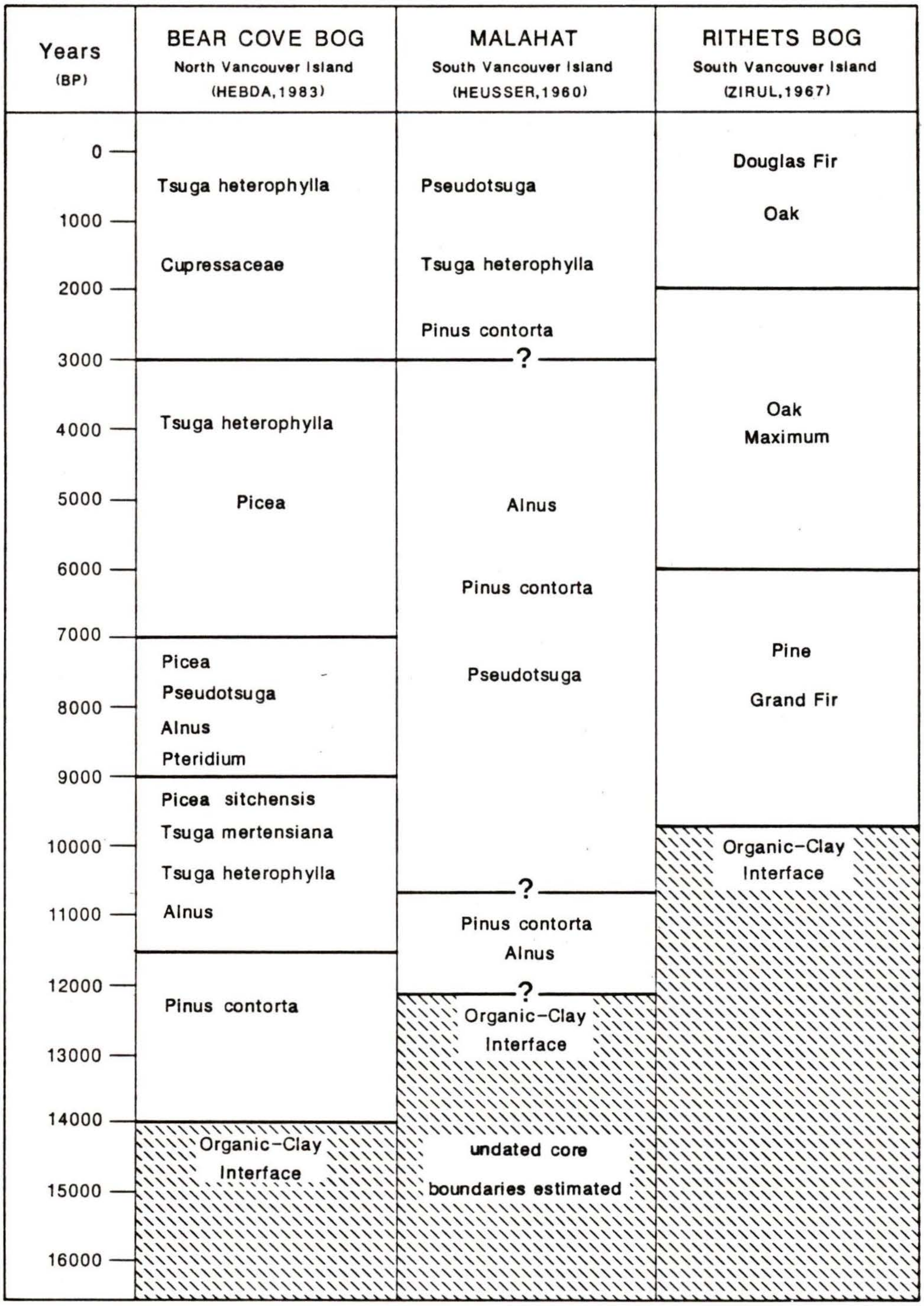
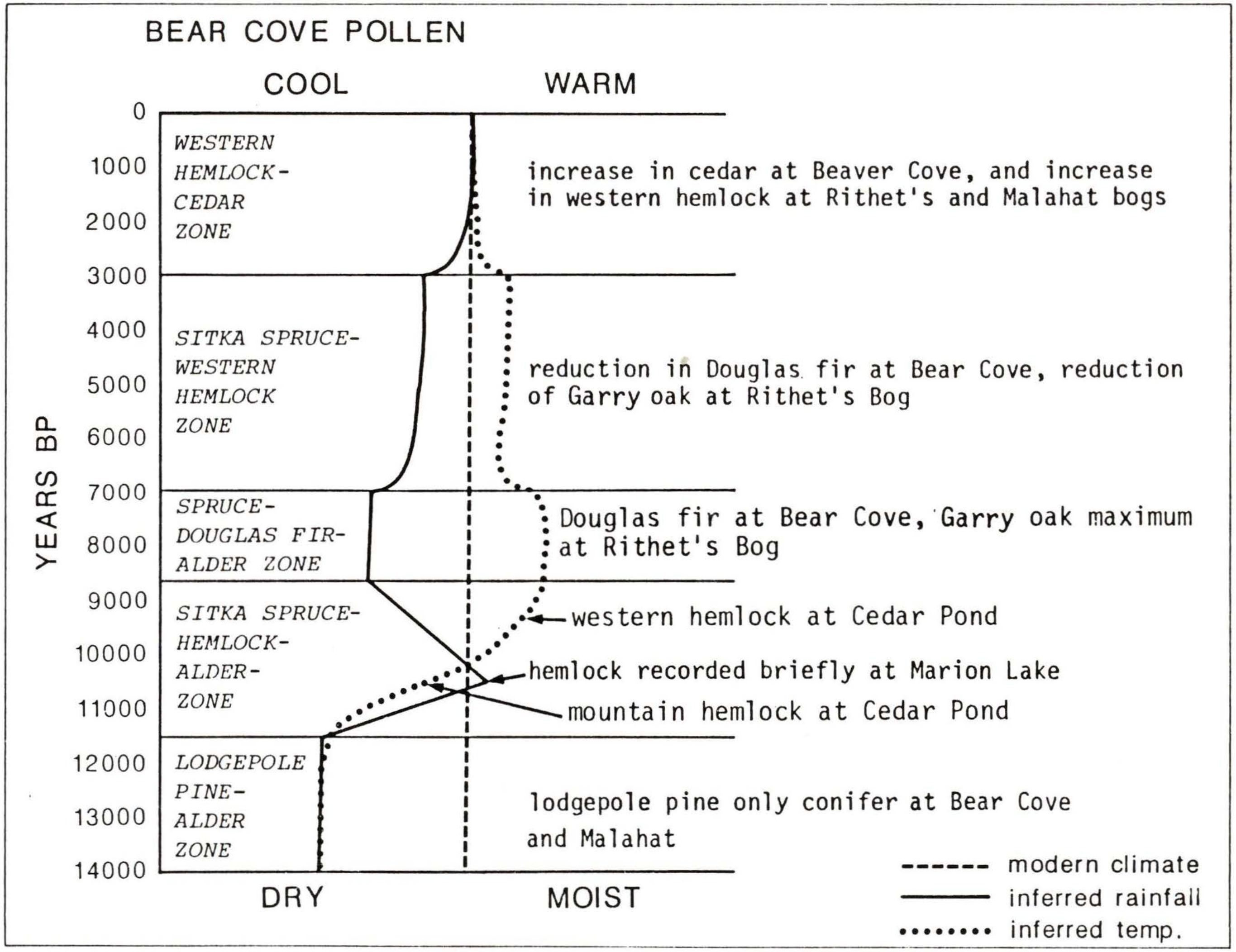

Years
(BP)
BEAR COVE BOG
North Vancouver Island
(HEBDA,1983)
MALAHAT
South Vancouver Island
(HEUSSER,1960)
RITHETS BOG
South Vancouver Island
(ZIRUL,1967)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
Tsuga heterophylla
Cupressaceae
Tsuga heterophylla
Picea
Picea
Pseudotsuga
Alnus
Pteridium
Picea sitchensis
Tsuga mertensiana
Tsuga heterophylla
Alnus
Pinus contorta
Organic-Clay
Interface
Pseudotsuga
Tsuga heterophylla
Pinus contorta
?
Alnus
Pinus contorta
Pseudotsuga
?
Pinus contorta
Alnus
?
Organic-Clay
Interface
undated core
boundaries estimated
Douglas Fir
Oak
Oak
Maximum
Pine
Grand Fir
Organic-Clay
Interface

Figure 7: Holocene Pollen Record from Bear Cove, Vancouver Island (from Hebda, 1983) and the Implied Climatic Changes


BEAR COVE POLLEN
COOL
WARM
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
YEARS BP
WESTERN HEMLOCK-CEDAR ZONE
SITKA SPRUCE-WESTERN HEMLOCK ZONE
SPRUCE-DOUGLAS FIR-ALDER ZONE
SITKA SPRUCE-HEMLOCK-ALDER-ZONE
LODGEPOLE PINE-ALDER ZONE
increase in cedar at Beaver Cove, and increase in western hemlock at Rithet's and Malahat bogs
reduction in Douglas fir at Bear Cove, reduction of Garry oak at Rithet's Bog
Douglas fir at Bear Cove, Garry oak maximum at Rithet's Bog
western hemlock at Cedar Pond
hemlock recorded briefly at Marion Lake
mountain hemlock at Cedar Pond
lodgepole pine only conifer at Bear Cove and Malahat
DRY
MOIST
------ modern climate
—— inferred rainfall
•••••••• inferred temp.

spruce) on northern Vancouver Island from 14,000 - 12,000 years BP. The implication of a dry climate on Vancouver Island following deglaciation is in contrast to the climatic periods proposed by Wright (1976). The contrasts in climate probably reflect regional differences.

The lodgepole pine-alder pollen zone at Bear Cove was replaced with a Sitka spruce-mountain/hemlock-alder zone (11,500 - 8800 BP). The presence of mountain hemlock in the first part of the zone indicated temperatures were lower than today. The replacement of mountain hemlock by western hemlock by 10,000 BP indicated a warming trend in the latter part of this zone. The co-dominance of Sitka spruce throughout this zone suggests rainfall had increased from the previous lodgepole pine-alder zone (Hebda, 1983). The climate of south-eastern Vancouver Island during this period was probably too dry and warm for western hemlock. Consequently, coastal Douglas-fir probably replaced lodgepole pine directly (Hansen, 1950). Zirul (1967) observed Garry oak and coastal Douglas fir during this period, which supports Hansen's hypothesis. A brief moist phase during this period is indicated by peaks of western hemlock at Marion Lake (Mathews, 1973), and grand fir in the lowlying areas of southern Vancouver Island (Zirul, 1967).

The warm and dry period known as the early Holocene xerothermic interval (Wright, 1976) was observed between 8800 - 3000 BP at Bear Cove (Hebda, 1983). Maximum temperatures and below normal precipitation are indicated between 8800 - 7000 BP by the co-dominance of coastal Douglas fir and western hemlock at Bear Cove (Hebda, 1983), and th dominance of Garry oak at Rithet's bog (Zirul, 1967).

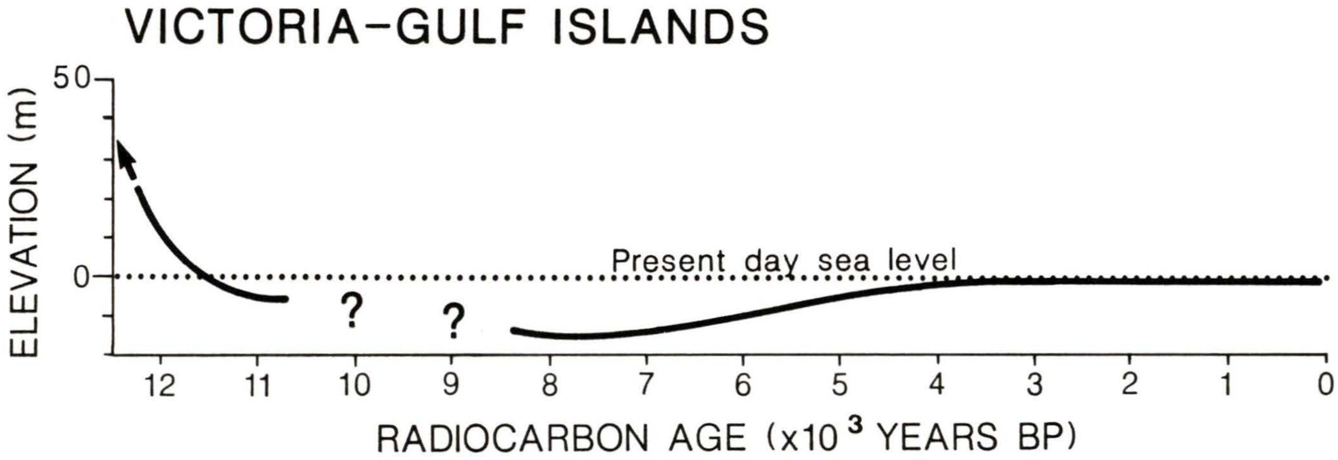
The early Holocene xerothermic interval continued until 3000 BP, with climatic conditions slightly cooler and wetter than before. Evidence for this moderating climate was the reduction, but continued presence of coastal Douglas fir at Bear Cove (Hebda, 1983), an increase coastal Douglas fir pollen and a decrease in Garry oak pollen in Rithet's bog (Zirul, 1967). Climatic conditions were still warmer and drier than today.

The last climatic adjustment resulted in the present day climate, which is wetter and cooler than the previous interval. The substitution of cedar for spruce on northern Vancouver Island (Hebda, 1983), and an increase in western hemlock and a decrease in coastal Douglas fir on southern Vancouver Island support the above premise (Heusser, 1960; Zirul, 1967).

2.9 HOLOCENE SEA LEVELS

Holocene sea levels for the coast of British Columbia have been delineated using ^{14}C data collected from coastal areas (Clague *et al*., 1982). The sea level for the Victoria area was approximately 25 m above the present datum 12,500 years B.P. (Figure 8), the period when the Langford Lake area was deglaciated (Clague, pers. comm.). Sea levels declined below the present datum during the early Holocene xerothermic interval, and then rose to the present datum. Based on the data presented by Clague *et al*. (1982) and the present datum of Langford Lake (61 m), marine intrusion into Langford Lake or its watershed did not occur during the Holocene period.

Figure 8: Sea Level Changes for Southern Vancouver Island Since the Vashon Glaciation (from Clague *et al*., 1982).


VICTORIA-GULF ISLANDS
ELEVATION (m)
50
0
Present day sea level
?
?
12
11
10
9
8
7
6
5
4
3
2
1
0
RADIOCARBON AGE (x10 3 YEARS BP)

3. METHODS

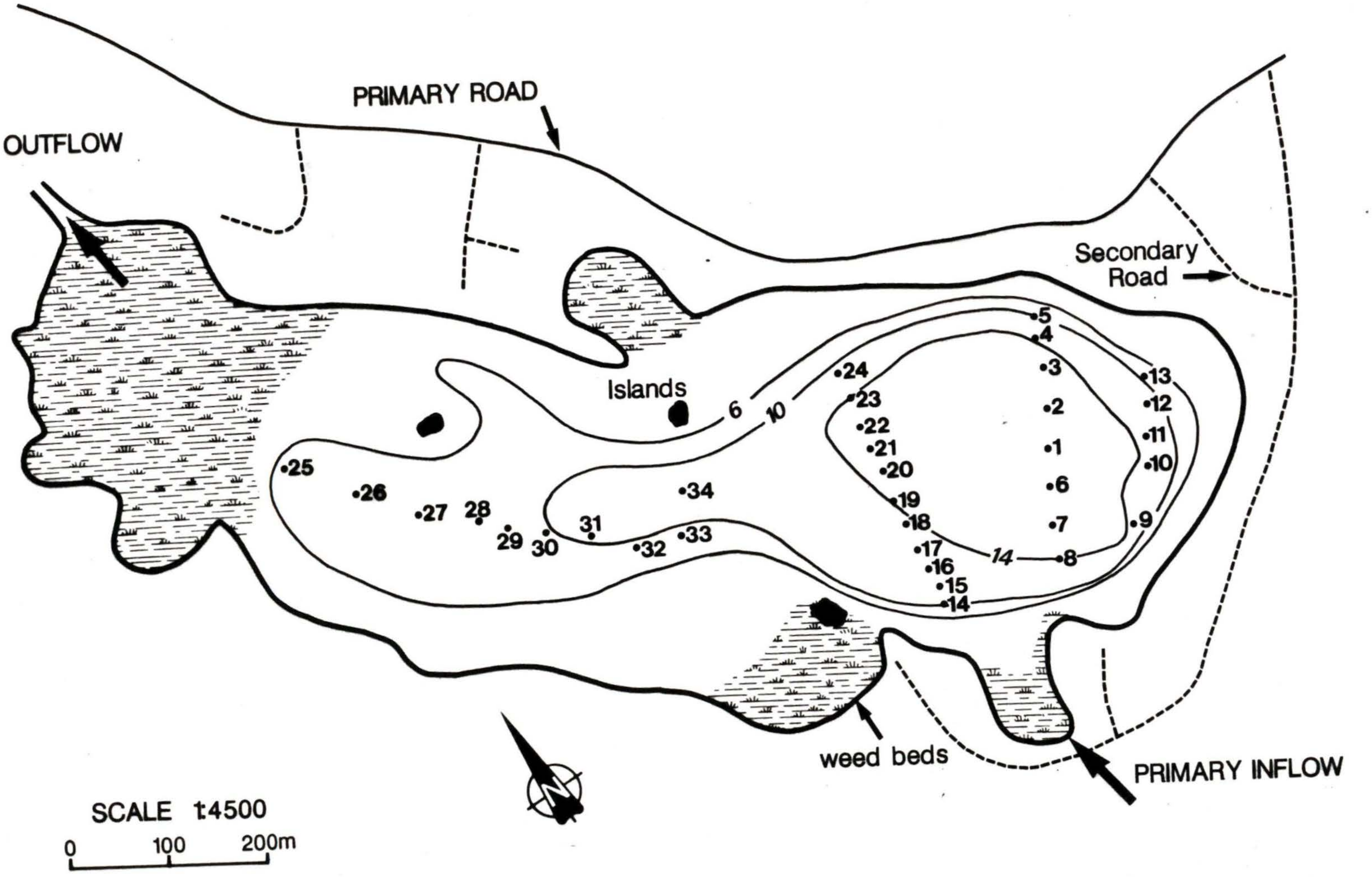
3.1 PROJECT DESIGN

An inexpensive semi-continuous corer was developed and used to obtain an complete core of the limnetic sediments from the deepest point in Langford Lake. A complete description of the corer design is included in Appendix 1 and published in McKean and Nordin (1986). The deepest point of the lake was chosen for core analysis because the site would provide the best representation of the limetic conditions of the lake (Pennington, 1981).

Cores of 8 and 12 m in length were collected from the deepest point in the lake in August, 1982 and August, 1983, respectively. The cores were transported to the University of Victoria, and subsampled within 3 weeks. The first core (8 m) was subsampled for chemical analyses every 20 cm along the core. The second core (12 m) was subsampled for chemical analysis every 5 cm from 0 to 2 m, and then every 20 cm to 12 m. Samples for fossil diatoms and pollen were collected every 5 and 20 cm respectively on both cores. The physical description of the core was completed with the assistance of Dr. R. Hebda of the Provincial Museum, Victoria, B.C. The physical and chemical results are discussed in this report: pollen and diatom samples have not been analyzed at this time.

Thirty-eight surface sediment samples were collected from Langford Lake in December, 1983 with an Ekman dredge from 34 sites (Figure 9). The sediments were carefully emptied into a plastic tray, where the top 5 cm was collected in an acid washed 220 mL plastic cup. Three replicate Ekman grabs were taken at sites 33 and 34. The results from stations 33 and 34 provided an estimate of within-site variability. The results from sites 1-34 provided data on the within-lake mean concentrations and variabilities, and the spatial distribution of the elements analyzed.

Figure 9: Sediment Sampling Stations on Langford Lake


PRIMARY ROAD
OUTFLOW
Secondary Road
Islands
6
10
14
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
weed beds
PRIMARY INFLOW
N
SCALE 1:4500
0
100
200m

3.2 PHYSICAL DESCRIPTION OF LAKE SEDIMENTS

I used the Troels-Smith classification system (translated by Birks and Birks, 1980) to describe the sediments. This system uses six major sediment categories: Humus, turfa, detritus, limus, argilla and grana. A summary of the classifications system is given in Table 5.

a) Substantia humosa. This is humous material that is derived above water, and is completely disintegrated organic material. It is blackish and homogeneous with no apparent structure. It dissolves in dilute alkali to give a very dark liquid. The material is so completely decomposed that it is not possible to ascertain whether the sediment, or part of it, is limus, turfa, or detritus.

b) Turfa (peat). This sediment consists of macroscopic plant remains, such as roots, stems, trunks, mosses, etc. It is formed mainly from underground plant parts, and parts connected to the root system. The underground parts are not exposed to oxidation, since they are generally rooted in a waterlogged environment. Turfa is divided into three types: moss, wood, or herbaceous material.

c) Detritus. In contrast to turfa, detritus consists of above ground parts of plants not directly attached to the roots. There are three major types of detritus. D. lignosus (wood), D. herbosus (herbaceous), D. granosus (wood and herbaceous < 2 mm but > 0.1 mm).

Detritus is easy to determine when it is found in lakes but is is often impossible to distinguish from turfa in peats unless microscopic examination of the sediment is made in the laboratory.

d) Limus. Limus is also known as gyttja, and is composed of particles or colloids < 0.1 mm in size. The particles are very small parts of plants, animals, and microorganisms together with marl and other precipitates. There are four main types of limus, L. detri-

Table 5
The Troels-Smith Scheme for the Determination of the Composition of Lake and Bog Sediments (from Birks and Birks, 1980).

Class	Symbol	Sediment	Description
Turfa	Tb	T. bryophytica	Peat moss
	Tl	T. lignosa	Wood peat; stumps, roots of ligneous plants
	Th	T. herbacea	Herbaceous peat; roots or rhizomes of herbaceous
Detritus	Dl	D. lignosus	Fragments of ligneous plants >2mm
	Dh	D. herbosus	Fragments of herbaceous plants >2mm
	Dg	D. granosus	Fragments of ligneous and herbaceous plants, and sometimes of animal fossils <2mm >ca. 0.1mm
Limus	Ld	L. detrituosus	Plants and animals or fragments (gyttja) particles <ca. 0.1 mm.
	Lso	L. siliceus organogenus	Diatoms, needles of sponge, siliceous skeletons, etc., of organic origin, or parts of these. particles <ca. 0.1mm.
	Lc	L. calcareus	Marl, not hardened. Particles <ca. 0.1 mm.
	Lf	L. ferrugineus	Iron oxide, Particles <ca. 0.1 mm.
Argilla	As	A. steatodes	Mineral particles <0.002 mm (clay)
	Ag	A. granosa	Mineral particles 0.002 to 0.06 mm (silt)
Grana	Ga	G. arenosa	Mineral particles 0.6 to 2mm (fine sand)
	Gs	G. suburralia	Mineral particles 0.6 to 2mm (coarse sand)
	Gg	G. glareosa	Mineral particles > 2mm (gravel)
Substantia humosa	Sh	Humous substance	Completely disintegrated organic substances and precipitated humic acids

tuosus, L. siliceus organogenes, L. calcareous, and L. ferrugineus.

e) Argilla. Argilla consists of mineral particles <0.06 mm in size. In comparison with limus it is heavier when dry, and it is plastic and not elastic when moist. There are two types of argilla, A. steatodes (clay), and A. granosa (silt).

f) Grana. Grana consists of mineral particles >0.06 mm in size. The grit can be felt when rolled between the fingers. The types of grana are divided according to size, G. arenosa (fine sand), G. suburralia (coarse sand), G. glareosa (gravel).

3.3 CHEMICAL DIGESTION/EXTRACTION PRODEDURES

Chemical analyses require the dissolution of the sediment components and the analysis of the supernatant. Individual elements can be associated with both organic and inorganic components of the sediments. Iron for example, can also be associated with organic matter, amorphous inorganic compounds (e.g. $Fe(OH)_3$), and a variety of minerals (e.g. strengite: $FePO_4$ $2H_2O$), and also be found within the lattice structure of clays and silica crystals. The method of sediment digestion prior to analysis determines the fraction(s) extracted. The more vigorous or harsh the digestion, the closer the result will be to the total content of the sample. Utilization of differential digestion techniques has been used frequently to partition the various important chemical fractions in soil or lake sediments (Bear, 1964).

All sediment analyses were completed at the Ministry of Environment and Parks Environmental Laboratory in Vancouver. The basic digestion procedure for sediments involved the addition of sufficient nitric acid to digest all the organic material. The mixture was boiled until dry, and perchloric acid was then added to digest the residue further. The perchloric acid-residue mixture was heated to its fuming point (210 °C) to maximize oxidization. The supernatant was decanted and diluted with a known quantity of distilled water, then analysed on an Applied Research Laboratories Ltd. (Missisauga, Ontario) Atomic Emission Spectrometer using Inductively Coupled Argon Plasma. The residues remaining after the digestion are primarily silica minerals, which contained varying amounts of metals within their lattice structures. Hydrofluoric acid (not used by the Environmental Laboratory) would be required to break down the silica minerals. The digestion procedures used by the Environmental Laboratory are designed to give an estimate of the environmentally available representative and transition elements of lake sediments (Barlow, pers. comm.).

Silicon from the Langford Lake sediments was analysed by the Environmental Laboratory but the results will not be discussed because the digestion/extraction methods produced inconclusive data. Samples of aluminosilicate clay and diatomaceous earth (Todd Creek, Victoria, B.C.) were sent to the Environmental Laboratory for analysis (McKean, unpubl.). Both silicon results were below 0.05 mg/g, when in fact the silica oxide content of both samples was well above 50% by weight (or 500 mg/g). The digestion technique of the Environmental Laboratory was not specific to diatom frustules or secondary silicate minerals; consequently, the silicon results from Langford Lake will not be presented or discussed.

3.4 ANALYTICAL VARIABILITY OF CHEMICAL ANALYSES

The sediment samples were analyzed for aluminum, calcium, carbon (organic and inorganic), iron, magnesium, manganese, nitrogen (Kjeldahl; TKN), phosphorus, and silica. The specific analytical techniques for each element are described by McQuaker (1976).

The Environmental Laboratory regularly determined analytical variability through the multiple analysis of standard reference materials from the National Bureau of Standards (Sylvestre, pers. comm.). The analytical variability of aluminum, calcium, iron, magnesium, manganese, and phosphorus using NBS standards was completed in the fall of 1986 (Table 6). All of the elements (measured on a dry weight basis) had analytical variability less than 5.5% (measured as the coefficient of variation of the NBS mean). Two NBS standards were tested for calcium, and the standard with the higher concentration (26 mg Ca/g (dry weight)) had the lower CV, which indicated that the analytical variability declined the farther the elemental concentrations were from the instrument's detection level. NBS standards were not tested for organic carbon, loss on ignition (LOI), or Kjeldahl nitrogen; however, analytical precision and accuracy were not expected to be different from the metals listed in Table 6 (Barlow, pers. comm.). Because all of the detectable elements discussed in this report were well above their detection levels, and the analytical tests were reproducible (except silicon), analytical variability was not an important consideration for the elements discussed in this report.

3.5 DATA ANALYSIS

All sediment data analysed by the Environmental Laboratory in Vancouver were entered on a Digital Equipment Corporation VAX computer at the Ministry of Environment and Parks. Data manipulation required the use of the VMS 4.4 operating system, and statistical package programs developed by SAS.

Cowgill and Hutchinson (1970) consider minerals expressed on a dry weight basis to be "uncorrected" for organic matter. The use of a correction factor to separate the organic and inorganic components can be justified because organic and inorganic matter originate from independent sources (Section 4.3.1). The sediments analysed by the Environmental Laboratory were analysed on a dry weight basis, but loss on ignition was also analysed, which allowed the inorganic results to be corrected for organics, and expressed as ash free dry weight (ash free dw).

Table 6
Analytical Variablity of the Environmental Laboratory using National Bureau of Standards Sediment Reference Materials.

Element		Concentration of NBS Standard	Average Deviation from NBS Standard[1]	Coefficient of Variation[2]
Aluminum	(mg/g)	3.6	0.168	4.6%
Calcium	(mg/g)	4.45	0.213	4.7%
Calcium	(mg/g)	26	0.741	2.8%
Iron	(mg/g)	66	3.0	5.3%
Magnesium	(mg/g)	6.7	0.079	1.2%
Manganese	(μg/g)	541	10.7	1.9%
Phosphorus	(μg/g)	467	18.1	3.9%

[1] Sylvestre (pers. comm).

[2] 100*(average deviation from standard/concentration of standard)

Statistical analysis of the chemical data included the calculation of Spearman correlation coefficients, and factor analysis using all the chemical parameters. Factor analysis was preferred to principal component analysis because the technique separated the total variance into common and unique variances in order to group the variables (Cureton and D'Agostina, 1983). The use of the total variance (principal component analysis), produces components that are more complex functions of the variables, and hence more difficult to interpret. The SAS factor analysis program was used with the varimax option. The varimax option should be used when three or more factors are used, because it distributes the total common variance over the rotated factors which avoids the development of a general factor (Cureton and D'Agostino, 1983).

4. RESULTS

4.1 PHYSICAL DESCRIPTION

One of the most important physical attributes of lake sediments is their visual appearance. The origin of the organic and inorganic constituents of sediment, and the decomposition and weathering processes that alter the constituents, determine the visual appearance of lake sediments (Birks and Birks, 1980). The cores collected from Langford Lake were described with the assistance of Dr. R. Hebda of the Provincial Museum (Table 7), using the sediment classification system developed by Troels-Smith (Section 3.2).

Langford Lake is divided into six distinct zones based on the physical description of the sediments (Table 7). A photographic record of the Langford Lake core from 6 to 12 m was completed immediately after extraction (Appendix 2). Zone P1 (11.99 - 12.09 m) represents the late-glacial period dominated by the erosion of clastic minerals (blue-grey clay) forming Argilla steatodes deposits (Table 5). Zone P2 (11.64 - 11.99 m) represents the interface between the post glacial period (P3) and the late-glacial period (P1). This zone is dominated by Limus detrituosus (gyttja), but zones of blue grey clay and some silt (11.91 m) are interspersed through this zone. The interface between Zone P2 and P3 is a distinct thin clay band at 11.64 m. Below 11.64 m, clastic materials are not observed and Limus detrituosus dominated. Within Zone P2, there is a trace of volcanic ash (11.76 m) from the Glacier Peak eruption 11,300 BP (Clague, pers. comm.). Glacier Peak is located south and east of Mount Rainier, Washington State, U.S.A.

Zone P3 (5.90 - 11.64 m) represents a period dominated by autochthonous organic production and the absence of clastic materials. The top of the zone is dominated by Limus detrituous that is slightly fibrous. The fibrous texture suggests some Detritus lignosus is mixed

TABLE 7
Physical Description of Langford Lake Core

Depth below Sediment-water Interface (cm)	Sediment Zone	Sediment Description
0 - 30	P6 Ld* + Lso	++unconsolidated organic ooze, scattered Douglas fir needles, dark brown.
30 - 300		++semi-consolidated organic ooze, or lake mud, dark brown gyttja
300 - 315	----------------	watery zone.
315 - 400	P5 Ld + Lso	++lake mud (gyttja), moderately consolidated,lighter colour than above, greyish specks especially below 360 cm, faint laminae begin begin to appear.
400 - 470		++lake mud, as above.
470 - 590	----------------	++slightly lighter in colour, but otherwise as above.
590 - 710		++slightly lighter in colour, denser and slimier.
720 - 810	Ld + Lso	++dark brown detrital peat with greyish discolouration, flecks of thin bands or of greyish material (diatoms) present.
		++725 cm: thin grey band (diatoms), laminae deformed (dragged down by sampling.
	P3	++807 cm: greyish discolouration.
810 - 908		++faintly fibrous textured, dark brown gyttja.
908 - 924	Ld + Dl	++watery, non-fibrous, green brown gyttja (but not gelatinous), poorly consolidated, slightly slimey and sticky.
924 - 974		++blackish brown gyttja with patches of grey discolouration, faintly fibrous texture.
974 - 989		++blackish brown gyttja.
989 - 990	----------------	++slightly discoloured (light brown), blackish brown gyttja.
990 - 991	P4 Tephra	++volcanic ash (Mazama).
991 - 997	----------------	++mottled ash and blackish brown gyttja.
997 - 1031	P3 (cont'd)	++black brown gyttja.
1031 - 1164	Ld	++blackish brown gyttja.
1164 - 1189	----------------	++blackish organic sediment, almost gyttja like.
		++1164 cm: thin clay layer.
		++1176 cm: trace of volcanic ash (Glacier Peak).
	P2	++1181 cm: thin clay layer.
1189 - 1191	Ld + As	++blue grey clay mixed with blackish silty organic sediment/fine grained, almost gyttja like.
1191 - 1199	----------------	++blackish silty organic sed./fine grained, almost gyttja like, mottled with traces of blue grey clay.
1199 - 1209	P1 As	++blue grey clay.

* See Table 4 for description of symbols.

with the L. detrituous. The bottom of Zone P3 (5.9 - 8.0 m) shifts from L. detrituous to L. siliceus organogenes. It is unclear if the shift constitutes a separte zone or a subzone of P3.

Zone P4 (9.91 - 9.97 m) represents the tephra deposited following the Mount Mazama eruption 6,600 years BP. This zone is different from the other zones in that it was created by a catrostrophic non-climatic event from outside the watershed.

Zones P3 and P5 are differentiated by sediment density. Sediments in Zone P5 (3.15 - 5.90 m) are much less dense in nature and darker brown in appearance. The sediments are still considered L. detrituous, but diatomaceous deposits are also common.

Zone P6 (0 - 3.15 m) is unconsolidated Limus detrituosus (ooze or gyttja). The sediments are dark-brown without any indication of diatomaceous deposits.

4.2 CORE DATES

Two dated volcanic events, and one ^{14}C date from Langford Lake are used to determine reference points on the 12 metre core. The Glacier Peak and Mount Mazama tephra deposits have been accurately dated at 11,300 and 6,600 BP (Clague, 1981). The depths of the volcanic tephra in Langford Lake are 11.76 and 9.9 m below the sediment-water interface, respectively. The results of the ^{14}C analysis at 11.85 m from Langford Lake was determined to be 10,640 ± 280 BP (Howes, pers. comm.). This date is 700 years after the Glacier Peak eruption, yet the sediments were deposited before the deposition of the tephra. The Glacier Peak date is considered to be more accurate than the ^{14}C date from Langford Lake, because the Glacier Peak date is based on ^{14}C analysis of wood contemporaneous with the eruption. Wood has a higher carbon content than lake sediments, providing greater analytical accuracy (Howes, pers. comm.).

4.3 CHEMICAL DESCRIPTION

4.3.1 General Sediment Description

The general chemical composition of the surface sediments of Langford Lake was 46% organic (measured by LOI, Table 8). Organic carbon and nitrogen accounted for approximately 50 and 5 percent of the organic component respectively. Hydrogen and oxygen are believed to be the other elements associated with organic matter (Wetzel, 1983). Other volatiles (mercury, ammonia, occluded water) are given off during heating, but their concentrations are typically less than 10% (Standard Methods, 1985).

The inorganic composition of the Langford Lake sediments was approximately 54% of the dry weight (100 - LOI). X-ray diffraction analysis (Appendix 3) showed that a small proportion (10% ash free dw) of the inorganic component was quartz (a primary silicate mineral, Lindsay, 1979). The small quantity of quartz indicates that the erosion of unweathered primary materials is small in the Langford Lake watershed. The lack of other crystalline minerals suggests that the majority of the inorganic fraction is amorphous in structure.

Other inorganic minerals such as iron hydroxide ($Fe(OH)_3$), variscite ($AlPO_4$ $2H_2O$) etc., are important components of the inorganic sediment, but do not constitute a significant proportion of the lake's sediments. Sulphur, iron, aluminum and calcium are the most abundant elements in the surface sediments of Langford Lake based on molarity (Table 8). The combination of all inorganic elements accounts for less than 5% of the sediment's dry weight. The remainder of the inorganic sediment is believed to be amorphous silica associated with diatom frustrules. Biogenic silica is not dissolved by the Ministry of Environment's digestion procedures; however, Brown (1978) observed high concentrations of diatom frustrules in Langford Lake. Consequently, the majority of the unaccounted inorganic fraction (80% of the

TABLE 8
Generalized Sediment Composition of the Surface Sediments of Langford Lake

ORGANIC COMPONENT*	46% of dw or 460 mg/g(dw)	
Carbon, organic	210 mg/g(dw) or	0.0175 moles/g
Nitrogen, Kjeldahl	21 mg/g(dw) or	0.0018 moles/g
Unaccounted (hydrogen, oxygen, etc.)	229 mg/g(dw)	
INORGANIC COMPONENT** All results below expressed on an ash free dw basis)	54% of dw or 540 mg/g(dw)	
Iron	28.5 mg/g or	0.0005 moles/g
Sulphur	27.0 "	0.00076 "
Calcium	17.5 "	0.00041 "
Aluminum	13.6 "	0.0005 "
Magnesium	3.7 "	0.00015 "
Phosphorus	1.9 "	0.00006 "
Manganese	0.8 "	0.00002 "
Titanium Zinc Lead Copper Vanadium Barium Strontium Chromium Nickel Molybdenum	= 1.0 mg/g (McKean, unpub.)	
Diatom frustules***	- 400 mg/g	
Quartz****	- 100 mg/g (or 10% dw)	

* equivalent to LOI.
** equivalent to (100-LOI).
*** estimated by subtraction (see text).
**** x-ray diffraction.

the inorganic fraction or 50% of the dry weight) is thought to represent amorphous silica oxide associated with diatom frustrules.

A summary of the generalized composition of the Langford Lake sediments based on dry weight is:

	% of dry weight
Organics (45%)	
Organic carbon	20%
Unidentified organics	20%
Kjeldahl nitrogen	5%
Inorganics (55%)	
Unaccounted (Biogenic silica)	40%
Quartz	10%
Amorphous elements	5%

4.3.2 Horizontal Distribution

Prior to the interpretation of the chemical data, an assessment of the within-site and within-lake data is required to ascertain the representativeness of a single sample or core from a site in the lake. Surface sediments from 34 sites (Figure 9) were collected on December 19, 1983, and chemically analysed (Appendix 4). The mean, standard deviation, and range of the results are summarized in Table 9.

a) Within-site Variability

The within-site coefficients of variation (CV) were calculated using the replicated data from sites 33 and 34 (Table 10). Inorganic carbon results were consistently below the 0.5 mg/g dw detection level, while manganese, organic carbon, loss on ignition (LOI), Kjeldahl nitrogen (TKN), and magnesium had within-site CV values below 2 percent. The remainder of the elements had within-site CV values below 6% (Table 10). The low within-site variability indicated the elements

TABLE 9

Surface Sediment Chemistry from Langford Lake: Means and Standard Deviations for Replicated Sites 33 and 34, and Sites 1-34 inclusive.

		Replicated Site 33 (n=3)		Replicated Site 34 (n=3)		Sites 1-34 (n=34)		
Parameter		Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Range
Aluminum	mg/g	6.76	0.19	6.84	0.21	7.27	1.13	5.63-9.92
Calcium	mg/g	10.30	0.26	9.63	0.14	9.09	1.37	6.85-11.70
Carbon, inorganic	mg/g	0.5	0.0	0.7	0.4	1.3	1.1	0.5-4.5
Carbon, organic	mg/g	247	3	237	5	209	40	111-283
Iron	mg/g	15.7	0.4	17.5	0.4	15.1	2.3	8.74-22.40
Magnesium	mg/g	1.90	0.02	1.98	0.01	1.96	0.4	1.36-3.37
Manganese	µg/g	452	4	407	2	398	110	79-672
Nitrogen-Kjeldahl	mg/g	26.2	0.3	24.4	0.1	20.8	4.3	11.1-28.2
Phosphorus	µg/g	1190	50	1076	30	985	130	767-1240
Loss on Ignition	%	53.3	0.6	51.4	0.2	46.0	8.0	24.3-60.6

see Figure 9 for site locations

TABLE 10

Within-Site and Within-Lake Coefficients of Variation for the Surface Sediments of Langford Lake

Parameter	Site 33 (n=3) (%)	Site 34 (n=3) (%)	Sites 1-34* (n=34) (%)
Aluminum	4.1	2.7	14.6
LOI	1.2	0.4	17.3
Carbon, organic	1.3	2.1	19.0
Iron	3.6	2.1	19.6
Magnesium	1.8	0.2	20.9
Nitrogen, Kjeldahl	1.1	0.2	22.5
Phosphorus	5.3	3.2	27.4
Calcium	3.5	1.3	28.8
Manganese	0.8	0.2	39.3

- CV calculated from mean and standard deviations (Table 9)

* replicated sites were averaged prior to statistical analysis

were relatively homogeneous on a site-specific basis, and one sample per site would be representative.

b) Within-lake Variability

Calculation of the CV using data from sites 1 - 34 (Figure 9) provided an estimate of the variability of each element within the lake's hypolimnetic sediments (Table 10). Aluminum had a CV of 14.6%, which was the lowest of the elements analysed. LOI, organic carbon, and iron all had CV values between 17 and 20%. The majority of the remaining elements had CV values between 20 and 30%, while manganese had the highest CV value at 39% (Table 10).

The within-lake variability of all elements was considered important, because the analytical and within-site variabilities were consistently lower. The spatial distribution of each element within the lake was examined to explain some of the observed within-lake variability (Figures 10 - 18), and factor and Spearman correlation analyses were used to group and quantify the observed spatial distributions (Tables 11 - 12).

c) Factor Analysis

Factor analysis grouped the surface sediments into 2 groups (Table 11). Factor 1 explained 73 percent of the total variance, and was the principal Factor for 6 of the 8 elements analysed (calcium, carbon (organic), iron, manganese, nitrogen (Kjeldahl), phosphorus). Factor 2 explained 14 percent of the total variance, and was the principal factor for the two remaining elements (aluminum and magnesium, Table 11).

d) Spatial Distribution

The concentrations of the elements (except inorganic carbon) were plotted on a bathymetric map of Langford Lake to observe their spatial distributions (Figures 10 - 18). Correlation analysis was also used to relate the site descriptions (water depth, distance from shore, and distance from weed beds) to the elements in an attempt to explain the factor analysis groupings, and quantify the observed spatial distributions (Table 13).

Water depth was negatively correlated with the elements explained by Factor 1 (Table 11). Calcium, Kjeldahl nitrogen, organic carbon and phosphorus all had high significant correlations with water depth ($r= -0.80$, Table 13). These elements themselves were highly correlated (Table 12), indicating they were all associated with the organic component of the sediment.

Aluminum, iron, and magnesium were poorly correlated with water depth ($r = {}^{-}0.46 - {}^{-}0.66$, Table 13); however, their spatial distributions appeared to be influenced by erosion from the shore (Figures 10, 13, and 15). The correlations of these elements with distance from shore were not significant (Table 13), presumably due to the difficulty of arbitrarily measuring distance from the site to the nearest erosion shore. The location of the main erosion shores relative to the sample sites would theoretically improve the correlations, but information on erosion from the various shores was not available.

4.3.3 Vertical Description

The within-site variability was sufficiently low to conclude that the core would be representative of a single site. The within-lake variability of most elements, however, was 15-30% of the overall mean for a lake; consequently minor fluctuations in core data would not be considered important. Rather, interpretation of the core data was restricted to trends, correlations, and the grouping of similar factors.

TABLE 11

Factor Analysis of the Surface Sediments from Langford Lake

Parameter	Factor 1	Factor 2
Aluminum	0.24	0.91
Calcium	0.79	0.58
Carbon, Organic	0.90	0.36
Iron	0.74	0.18
Loss on Ignition	0.92	0.33
Magnesium	0.20	0.92
Manganese	0.91	0.08
Nitrogen, Kjeldahl	0.92	0.21
Phosphorus	0.90	0.35
Eigenvalue	6.60	1.28
Proportion of Common Variance	0.73	0.14

TABLE 12

Spearman Correlation Coefficients for the Surface Sediment Elements*
from Langford Lake

	Al	Ca	C (organic)	Fe	LOI	Mg	Mn	TKN
Calcium	0.69							
Carbon, organic	0.52	0.95						
Iron	0.37	0.59	0.65					
LOI	0.50	0.94	0.98	0.67				
Magnesium	0.79	0.68	0.51	0.36	0.48			
Manganese	0.33	0.74	0.81	0.68	0.82	0.27		
Nitrogen, Kjeldahl	0.40	0.84	0.96	0.67	0.92	0.39	0.80	
Phosphorus	0.55	0.93	0.95	0.64	0.94	0.47	0.84	0.91

* n = 34

- All results as mg/g ash free dry weight basis except LOI (%), organic carbon and Kjeldahl nitrogen (dw basis).

TABLE 13

Spearman Correlation Coefficients for the Surface Sediment Results with Water Depth, Distance from Shore, and Distance from Aquatic Macrophyte Beds

Element	Water Depth	Distance from Shore	Distance from Aquatic Macrophyte Beds
Aluminum	-0.66**	-0.30	0.28
Calcium	-0.89**	0.25	0.31
Carbon, organic	-0.82**	0.35*	0.32
Copper	-0.30	0.36*	0.32
Iron	-0.46*	0.16	0.10
Lead	0.01	-0.36*	0.25
LOI	-0.82**	0.35*	0.34*
Magnesium	-0.63**	-0.18	0.17
Manganese	-0.73*	0.42*	0.40*
Nitrogen, Kjeldahl	-0.80**	0.42*	0.35*
Phosphorus	-0.82**	0.38*	0.40*
Zinc	-0.49*	-0.11	0.10

All results correlated on an ash free dry weight basis except LOI(%) and organic carbon and Kjeldahl nitrogen (dry weight basis).

* $0.001 < P < 0.05$
** $P < 0.001$

Figure 10: Aluminum Concentrations (mg/g ash free dw) in the Surface Sediments of Langford Lake

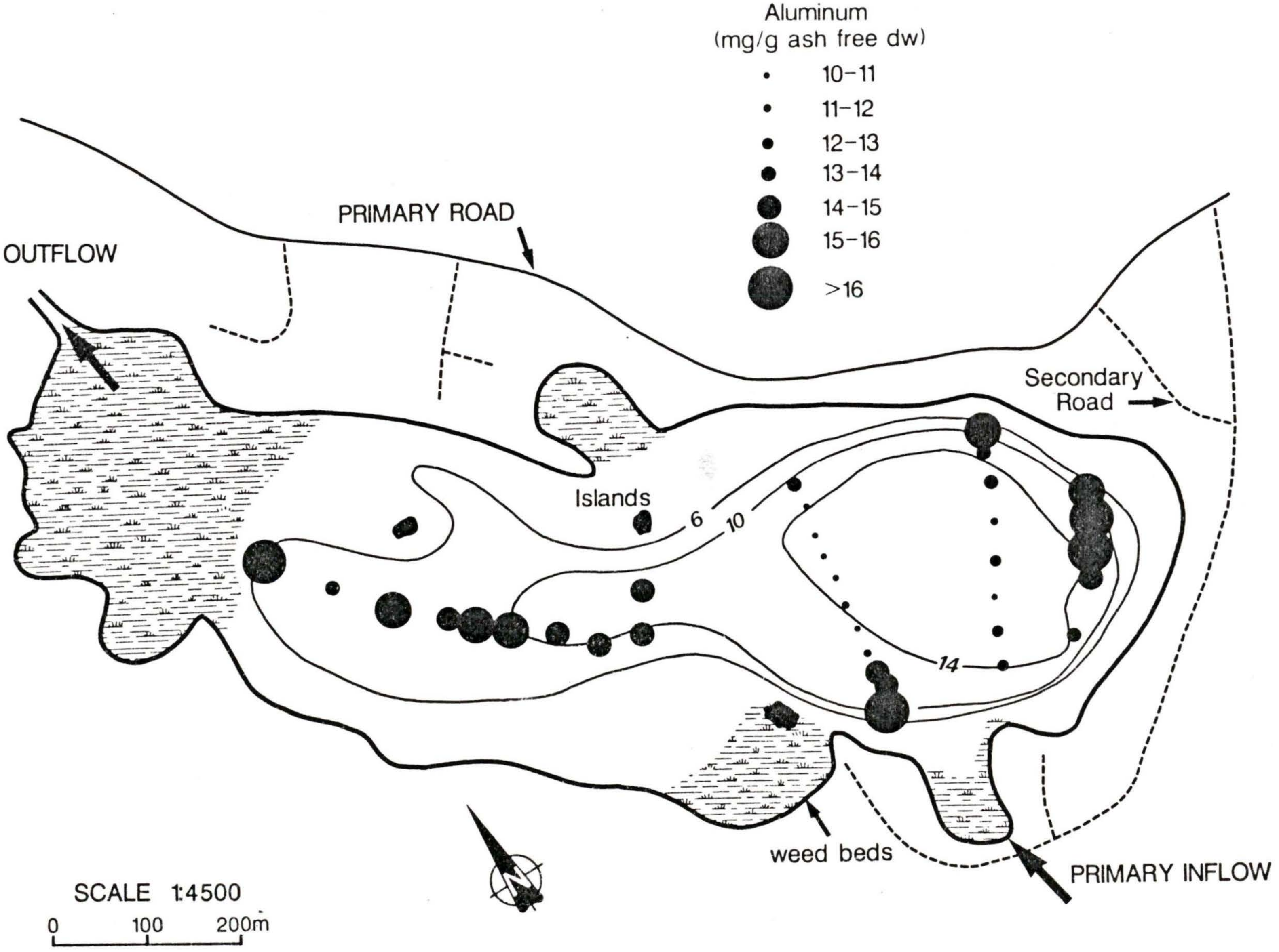

Aluminum
(mg/g ash free dw)
10–11
11–12
12–13
13–14
14–15
15–16
>16
PRIMARY ROAD
OUTFLOW
Secondary Road
Islands
6
10
14
weed beds
PRIMARY INFLOW
SCALE 1:4500
0
100
200m

Figure 11: Calcium Concentrations (mg/g ash free dw) in the Surface Sediments of Langford Lake

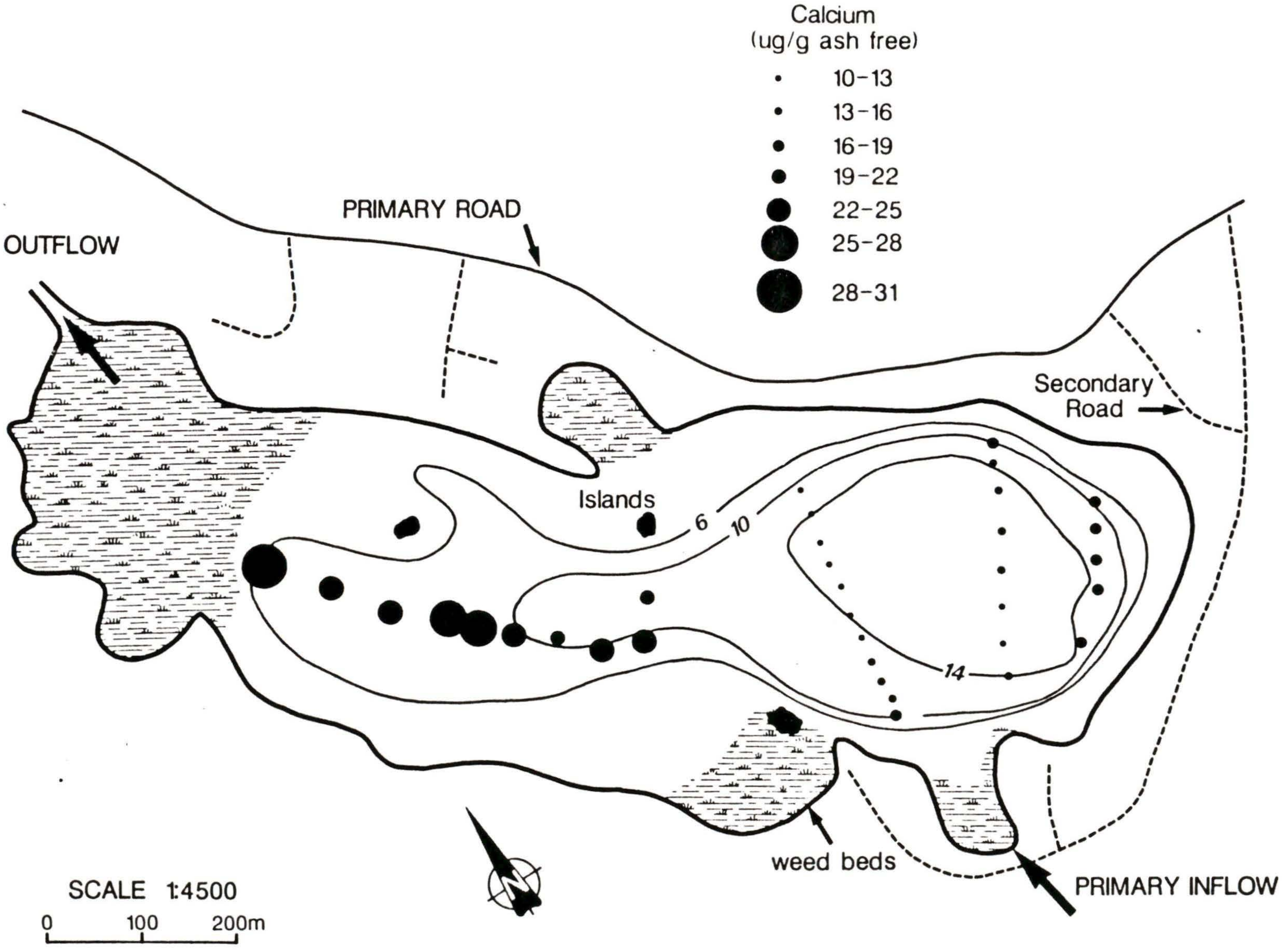

Calcium
(ug/g ash free)
• 10-13
• 13-16
● 16-19
● 19-22
● 22-25
● 25-28
● 28-31
PRIMARY ROAD
OUTFLOW
Secondary Road
Islands
6
10
14
weed beds
PRIMARY INFLOW
SCALE 1:4500
0
100
200m

Figure 12: Carbon (organic, mg/g dw) in the Surface Sediments of Langford Lake

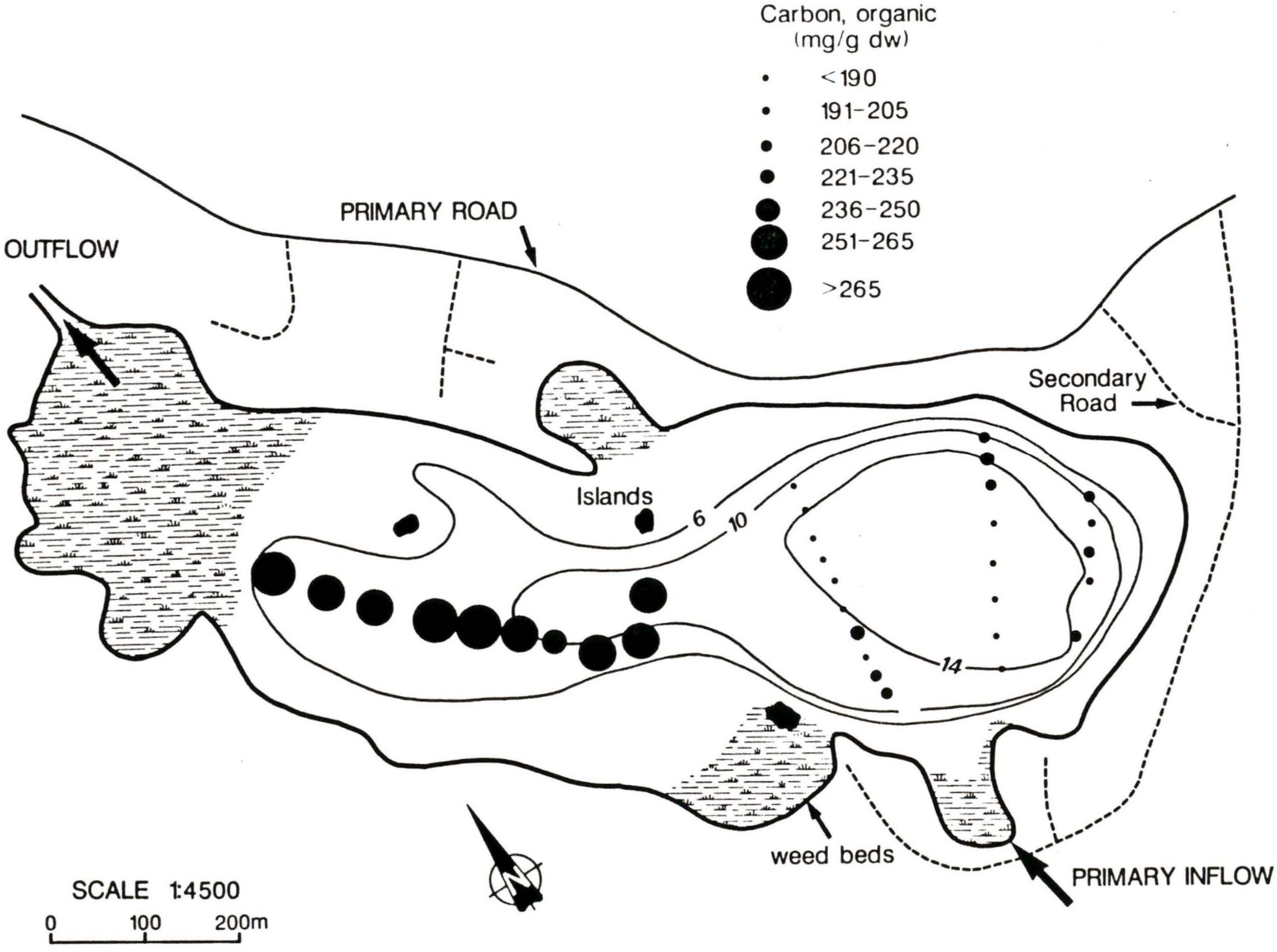

Carbon, organic
(mg/g dw)
• <190
• 191-205
● 206-220
● 221-235
● 236-250
● 251-265
● >265
PRIMARY ROAD
OUTFLOW
Secondary Road
Islands
6
10
14
weed beds
PRIMARY INFLOW
SCALE 1:4500
0 100 200m

Figure 13: Iron Concentrations (mg/g ash free dw) in the Surface Sediments of Langford Lake

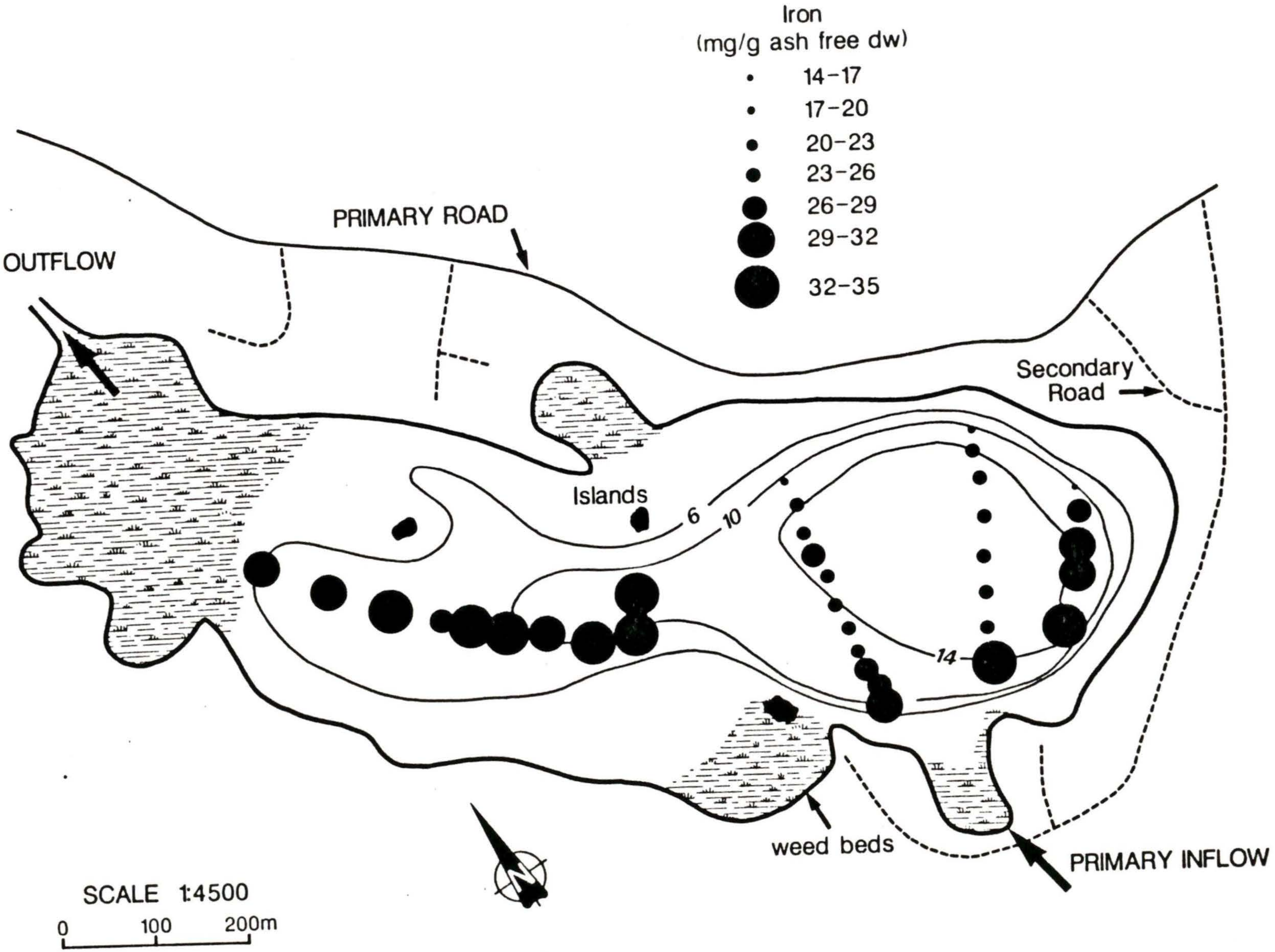

Iron
(mg/g ash free dw)
14–17
17–20
20–23
23–26
26–29
29–32
32–35
PRIMARY ROAD
OUTFLOW
Secondary Road
Islands
6
10
14
weed beds
PRIMARY INFLOW
SCALE 1:4500
0
100
200m

Figure 14: Loss on Ignition (%) in the Surface Sediments of Langford Lake

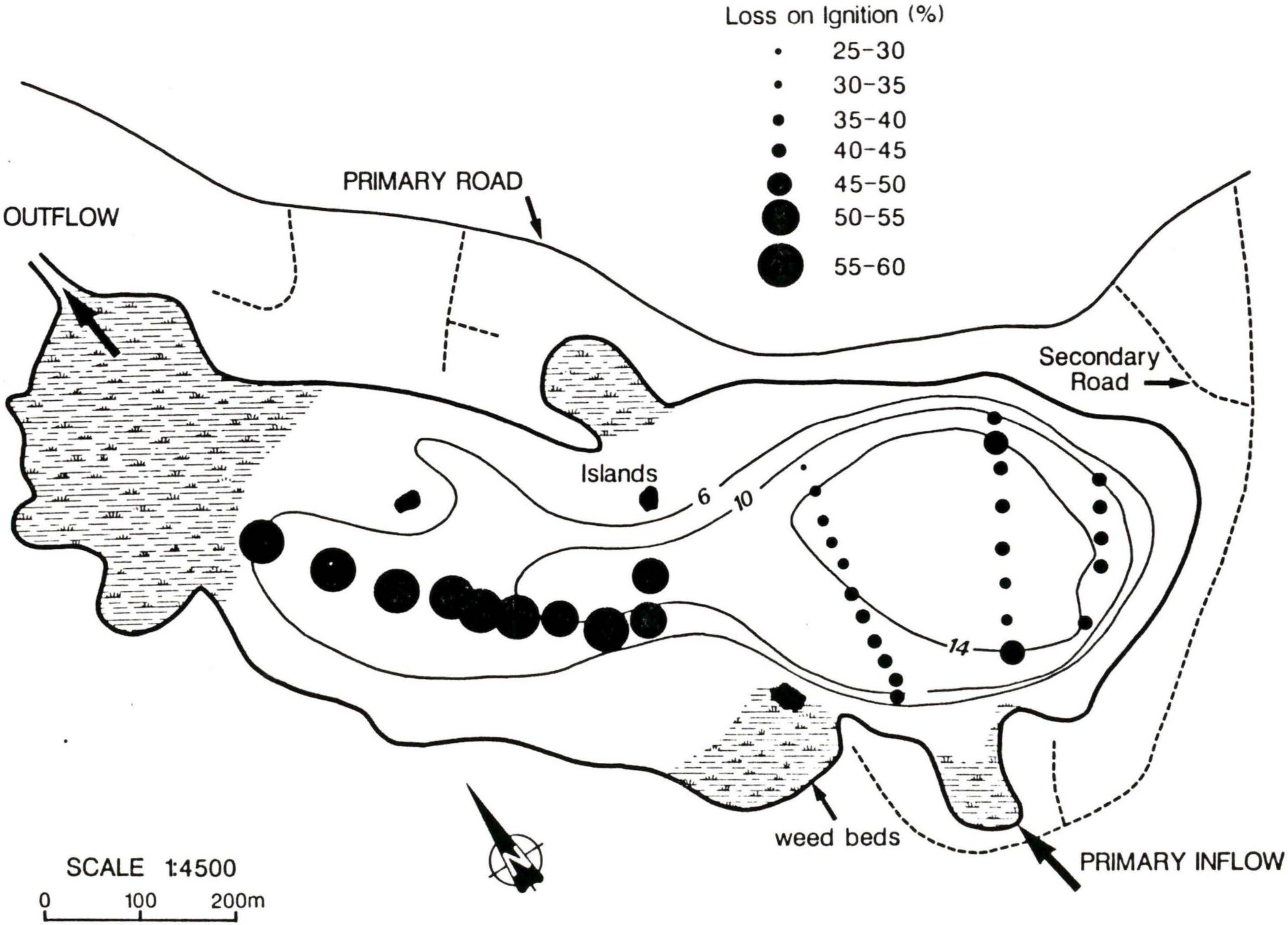

Loss on Ignition (%)
• 25-30
• 30-35
● 35-40
● 40-45
● 45-50
● 50-55
● 55-60
PRIMARY ROAD
OUTFLOW
Secondary Road
Islands
6
10
14
weed beds
PRIMARY INFLOW
SCALE 1:4500
0
100
200m
N

Figure 15: Magnesium Concentrations (mg/g ash free dw) in the Surface Sediments of Langford Lake

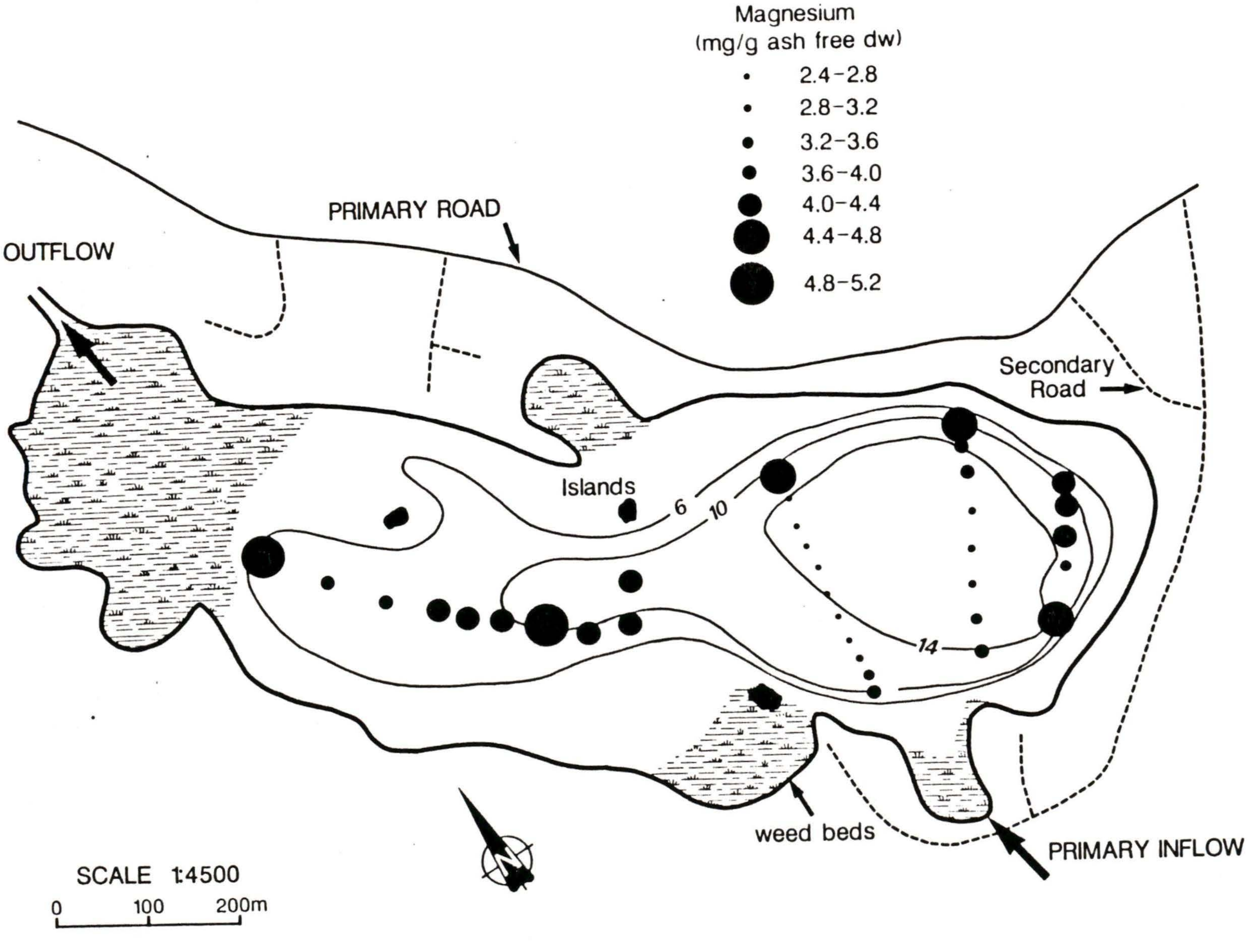

Magnesium
(mg/g ash free dw)
2.4-2.8
2.8-3.2
3.2-3.6
3.6-4.0
4.0-4.4
4.4-4.8
4.8-5.2
PRIMARY ROAD
OUTFLOW
Secondary Road
Islands
6
10
14
weed beds
PRIMARY INFLOW
SCALE 1:4500
0
100
200m

Figure 16: Manganese Concentrations (µg/g ash free dw) in the Surface Sediments of Langford Lake

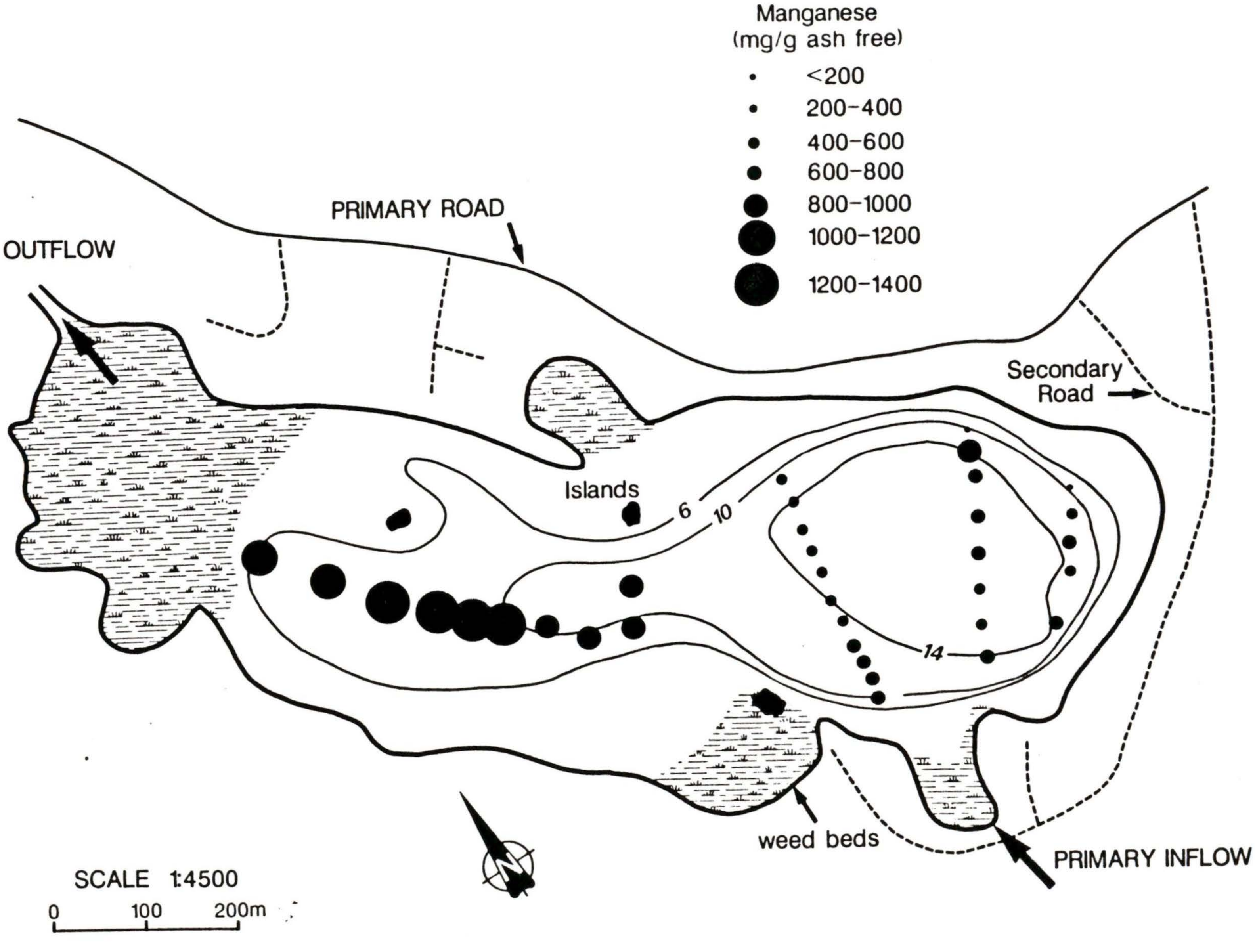

Manganese
(mg/g ash free)
<200
200–400
400–600
600–800
800–1000
1000–1200
1200–1400
PRIMARY ROAD
OUTFLOW
Secondary
Road
Islands
6
10
14
weed beds
PRIMARY INFLOW
SCALE 1:4500
0
100
200m

Figure 17: Nitrogen (Kjeldahl, mg/g dw) in the Surface Sediments of Langford Lake

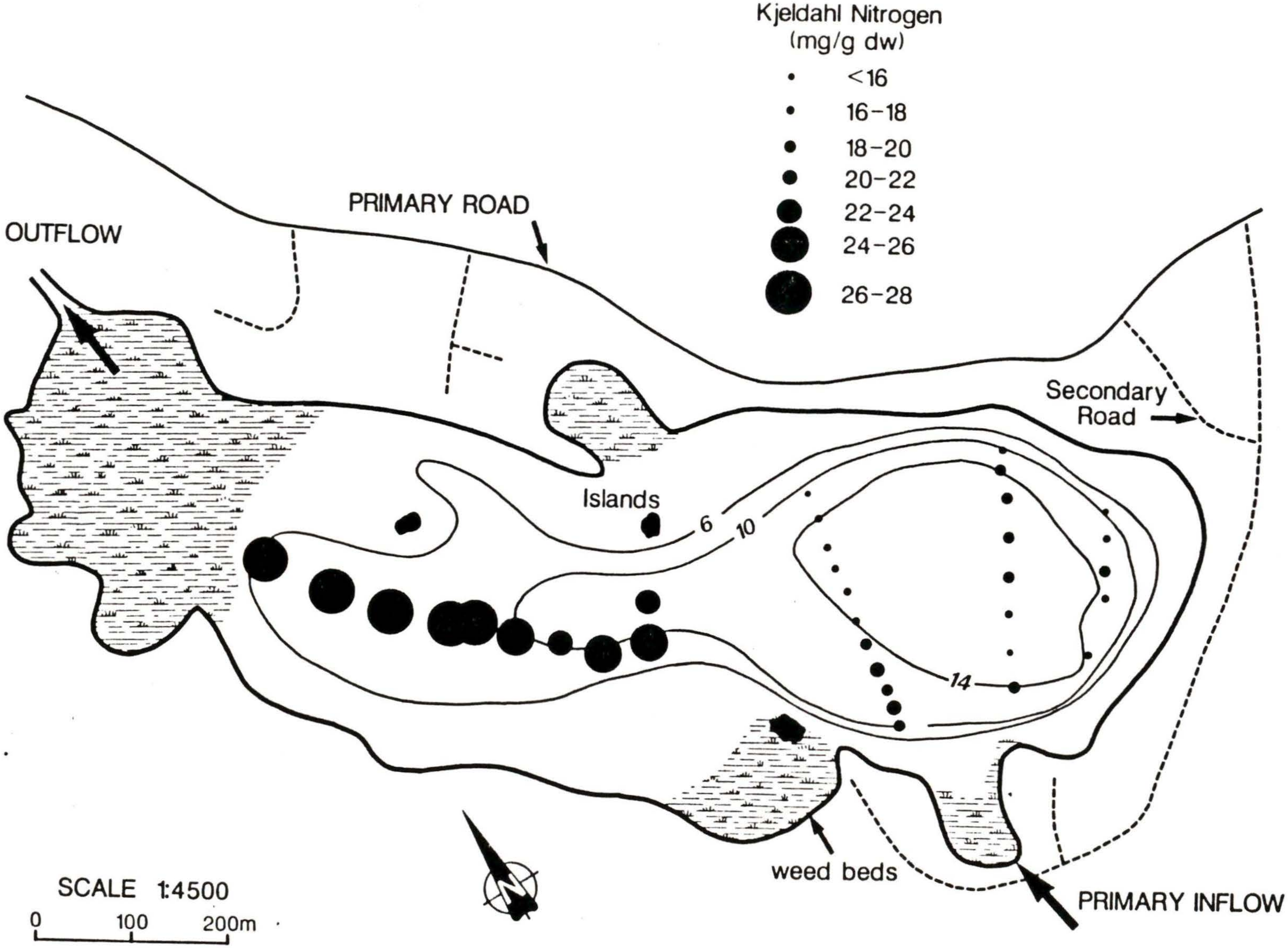
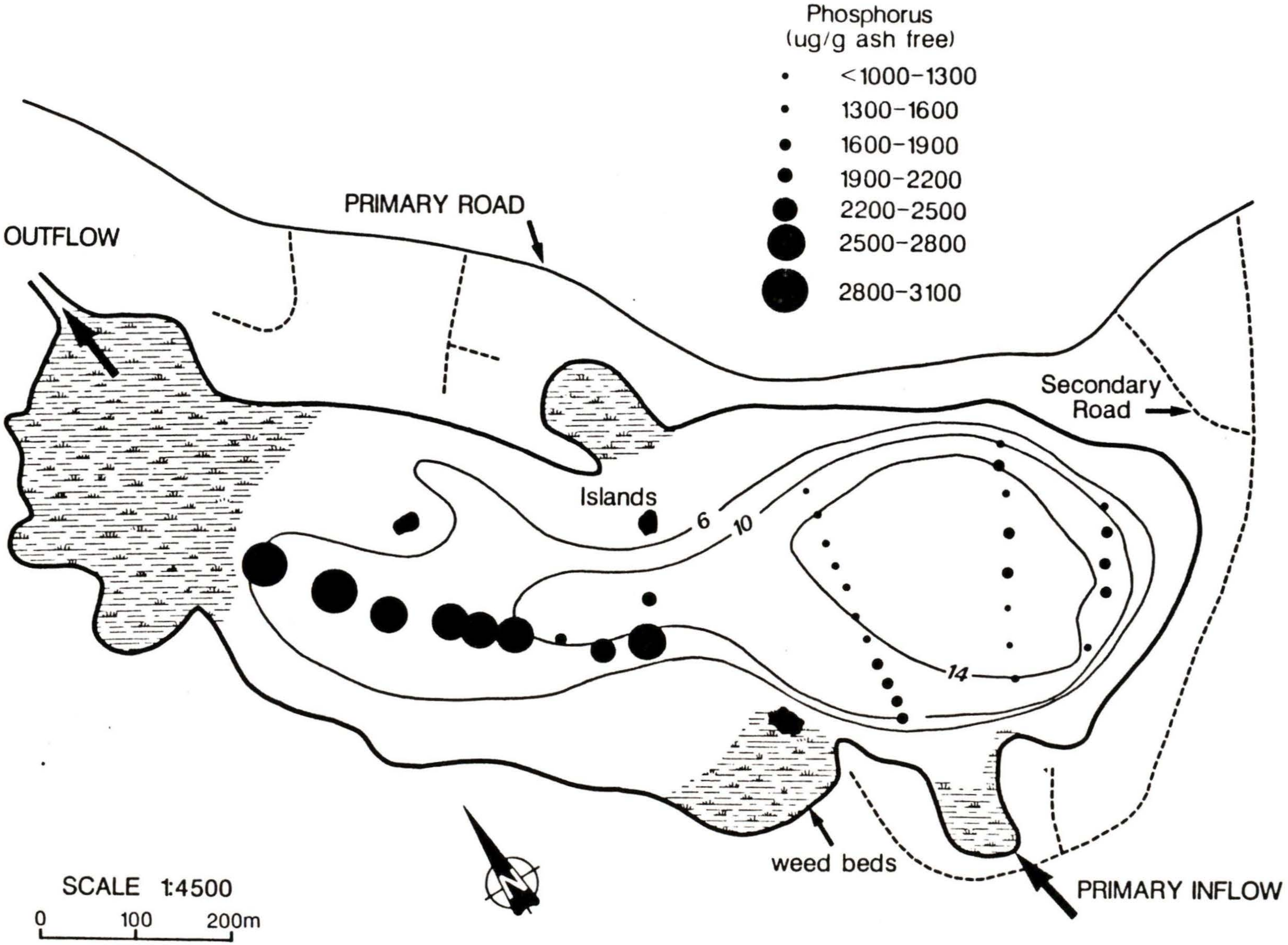

Kjeldahl Nitrogen
(mg/g dw)
<16
16–18
18–20
20–22
22–24
24–26
26–28
PRIMARY ROAD
OUTFLOW
Secondary Road
Islands
6
10
14
weed beds
PRIMARY INFLOW
SCALE 1:4500
0
100
200m

Figure 18: Phosphorus Concentrations (μg/g ash free dw) in the Surface Sediments of Langford Lake


Phosphorus
(ug/g ash free)
• <1000-1300
• 1300-1600
● 1600-1900
● 1900-2200
● 2200-2500
● 2500-2800
● 2800-3100
PRIMARY ROAD
OUTFLOW
Secondary Road
Islands
6
10
14
weed beds
PRIMARY INFLOW
SCALE 1:4500
0
100
200m
N

a) Comparison of Cores

The vertical chemical distributions in Langford Lake were studied from the analysis of two cores (Appendix 5 and 6) taken from the deepest point in the lake. Figures 19 - 21 compare the manganese, phosphorus, and Kjeldahl nitrogen concentrations from both cores. The concentration and trends in manganese from both cores were in excellent agreement with each other. Calcium, aluminum, iron, and magnesium also had similar concentrations and trends between cores. The agreement of these elements from the two cores gives additional support to the representativeness of a single core for the chemical analysis of a site, and the ability of the corer to take long reproducible cores.

The vertical distributions of phosphorus and Kjeldahl nitrogen were not identical as the parameters discussed above (Figures 20 and 21). The phosphorus and Kjeldhal nitrogen concentrations in core #2 were approximately 10% higher. Although the consistency of the difference indicates discrepancies in batch analytical results for those parameters, the trends, and the interpretation of those trends, are similar in both cores.

b) Factor Analysis

Factor analysis was used to group elements in core #2 -- the 12 metre core. The factor analysis, using the procedures outlined in Section 3.5, grouped the elements into two groups (Table 14). Factor 1 explained 51 percent of the core's total variance, and accounted for four of the eight elements analyzed. The four elements of Factor 1 (Kjeldahl nitrogen, calcium, phosphorus, and organic carbon) were all highly inter-correlated (Table 15), which indicated they were associated with the organic fraction of the sediment.

Factor 2 explained 42 percent of the core's total variance, and accounted for the remaining four elements (Table 14). Aluminum, iron,

Figure 19: Manganese Concentrations (μg/g ash free dw) from both Cores as a Function of Sediment Depth in Langford Lake.

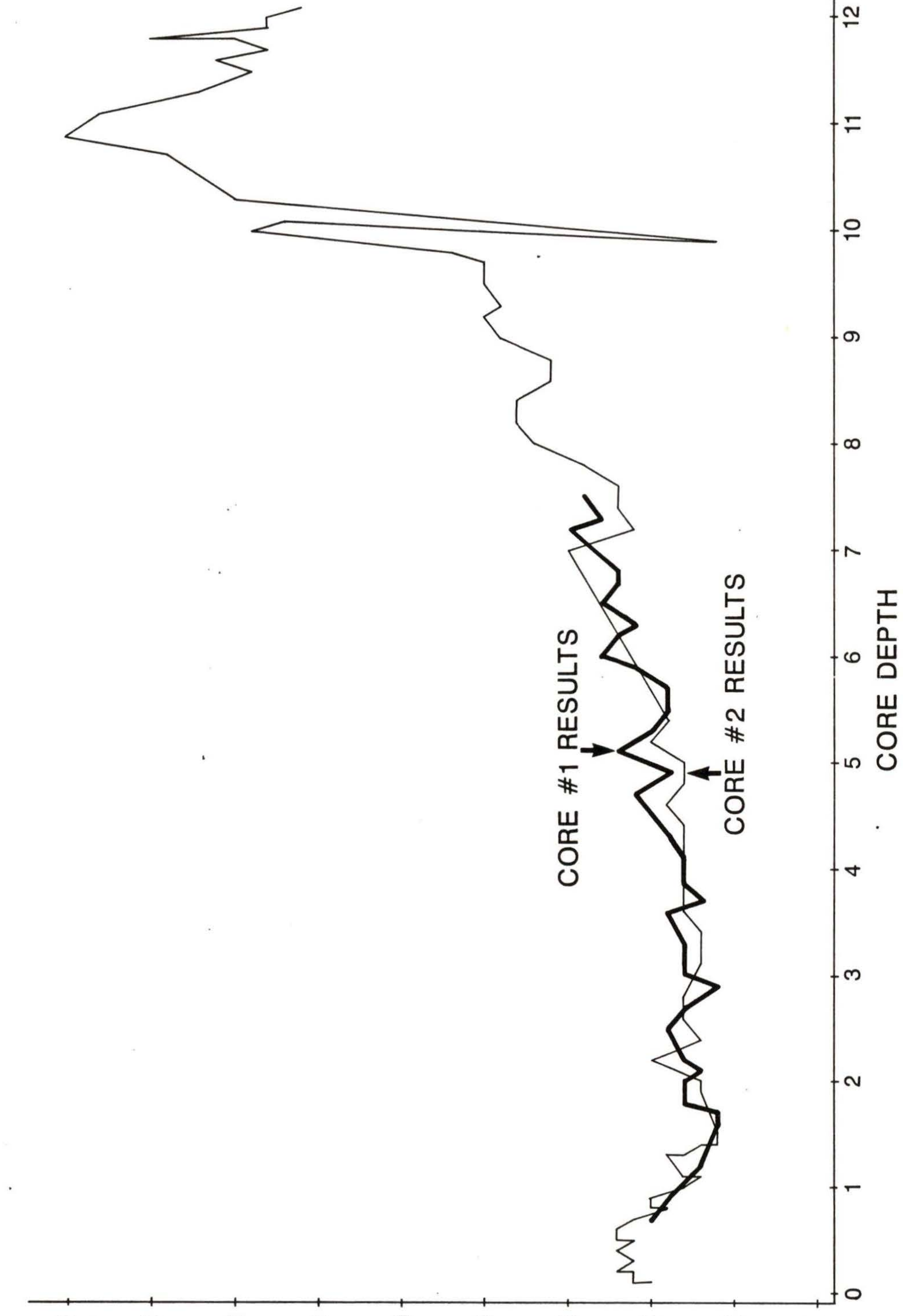

MANGANESE (µg/g ash free d w)
0
200
400
600
800
1000
1200
1400
1600
1800
CORE DEPTH
0
1
2
3
4
5
6
7
8
9
10
11
12
CORE #1 RESULTS
CORE #2 RESULTS

Figure 20: Phosphorus Concentrations (µg/g ash free dw) from both Cores as a Function of Sediment Depth in Langford Lake.

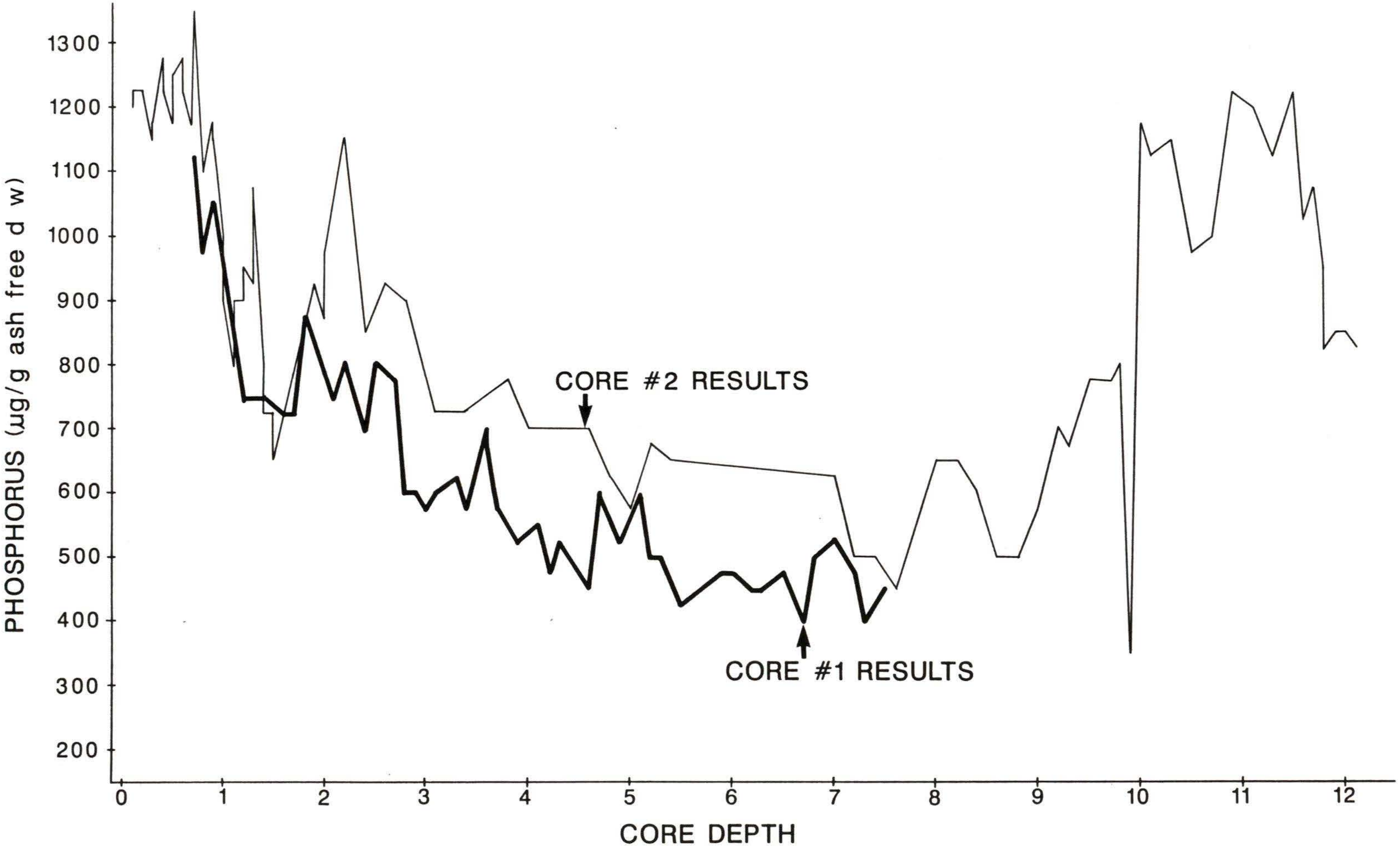
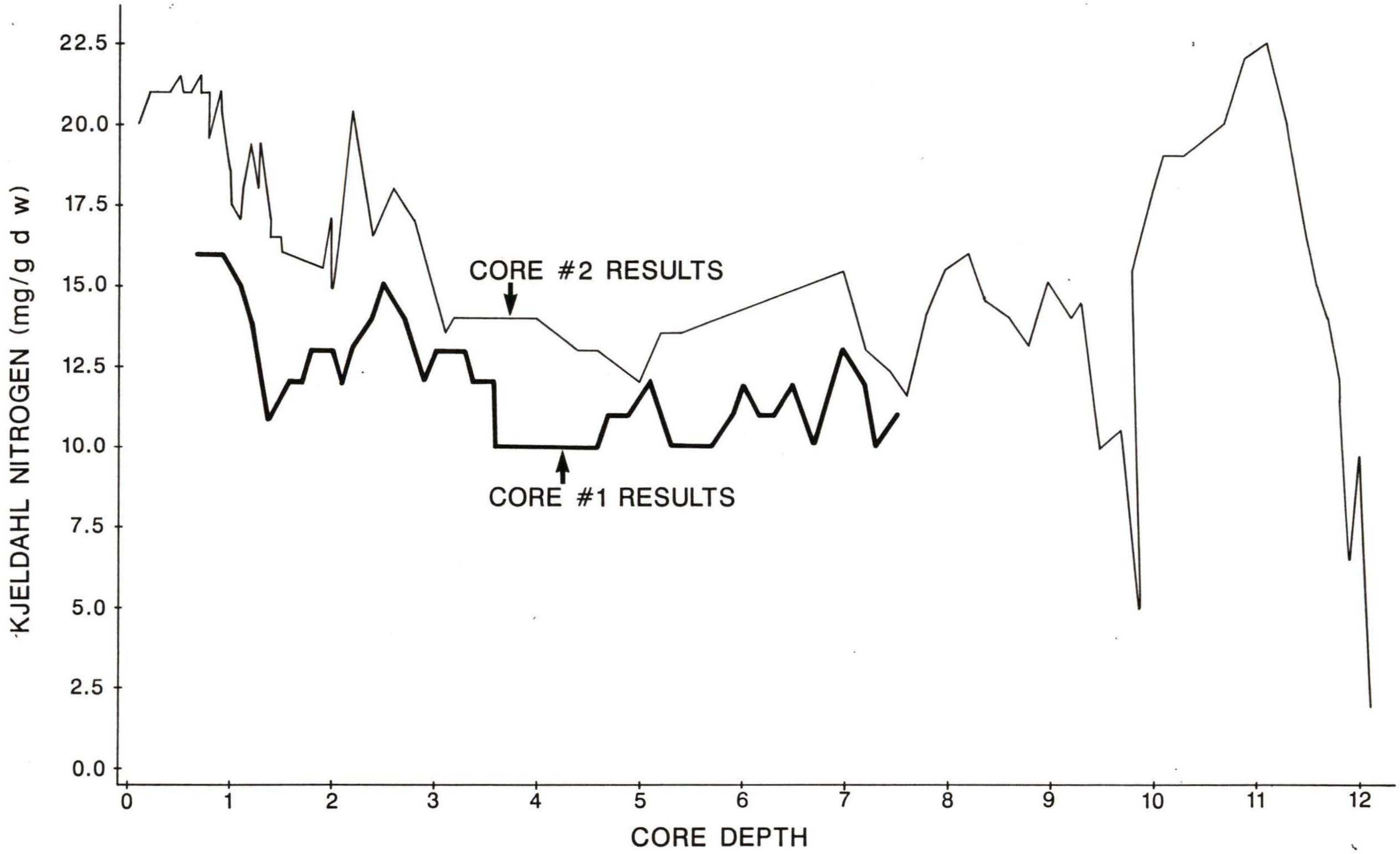

PHOSPHORUS (μg/g ash free d w)
1300
1200
1100
1000
900
800
700
600
500
400
300
200
CORE #2 RESULTS
CORE #1 RESULTS
0
1
2
3
4
5
6
7
8
9
10
11
12
CORE DEPTH

Figure 21: Nitrogen (Kjeldahl, mg/g dw) from both Cores as a Function of Sediment Depth from Langford Lake


KJELDAHL NITROGEN (mg/g d w)
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0
1
2
3
4
5
6
7
8
9
10
11
12
CORE DEPTH
CORE #2 RESULTS
CORE #1 RESULTS

magnesium, and manganese represent the inorganic elements whose sediment concentrations are governed by the degree of erosion or weathering of minerals in the watershed (See Section 5).

c) Stratigraphy

The vertical stratigraphy of the Langford Lake sediments is divided into six distinct zones (P1 - P6) based on the physical description of the sediments (Section 3.2). The physical zones were superimposed over the chemical results (Figures 22 - 30), and where possible, compared to the contemporaneous vegetative and climatic conditions.

The first Zone (Pl) occurs immediately after deglaciation and represents the blue-grey clay layer beneath the organic sediments (Appendix 2). The chemical analysis of the clay is restricted to one analysis at 12.05 m. Clays are typically composed of aluminosilicate minerals (Bear, 1964). The high concentrations of aluminum and magnesium (33 and 16 mg/g ash free dw, respectively) in Zone P1 indicates they are associated with the eroded secondary clay minerals (Figures 22 and 27). The concentrations of the other inorganic elements (iron, manganese, and phosphorus) in this zone were depressed by the high concentrations of aluminosilicates (Figures 26, 28, and 30). Autochthonous organic production and sedimentation in Langford Lake was probably insignificant during this period because the turbidity created by the clay particles in the glacial runoff would create light limited conditions for phytoplankton. The organic carbon concentration in the clay was 15 mg/g (dw), which was the lowest in the Holocene record. The other elements associated with the organic fraction (calcium, and Kjeldahl nitrogen) are also low (Appendix 4).

The second zone (P2, 11.4 -12.0 m) represents the transition from the late-glacial period (P1) to a post-glacial period (P3). Organic concentrations increased from a low of 15 mg/g (dw) at the beginning of

TABLE 14

Factor Analysis of the Core Data from Langford Lake

	Factor 1	Factor 2
Aluminum	-0.11	0.98
Calcium	0.92	0.22
Carbon, Organic	0.97	-0.12
Iron	-0.04	0.98
Loss on Ignition	0.96	-0.24
Magnesium	-0.17	0.96
Manganese	0.21	0.91
Nitrogen, Kjeldahl	0.96	-0.27
Phosphorus	0.84	0.22
Eigenvalue	4.56	3.74
Proportion of Common Variance	0.51	0.42

TABLE 15

Spearman Correlation Coefficients* for the Elements Analysed from Core #2, Langford Lake

	Al	Ca	C (organic)	Fe	LOI	Mg	Mn	TKN
Calcium	0.13							
Carbon, organic	-0.24	0.84						
Iron	0.94	0.15	-0.13					
LOI	-0.35	0.81	0.98	-0.26				
Magnesium	0.97	0.04	-0.29	0.94	-0.40			
Manganese	0.82	0.41	0.16	0.90	0.02	0.78		
Nitrogen, Kjeldahl	-0.37	0.79	0.96	-0.29	0.98	-0.41	-0.04	
Phosphorus	0.16	0.76	0.71	0.15	0.70	0.14	0.21	0.75

* Sample size = 84.

* Significance level $P < 0.05 = 0.215$
$P < 0.01 = 0.280$

Figure 22: Aluminum Concentrations (mg/g ash free dw) from Core#2 as a Function of Sediment Depth for Langford Lake

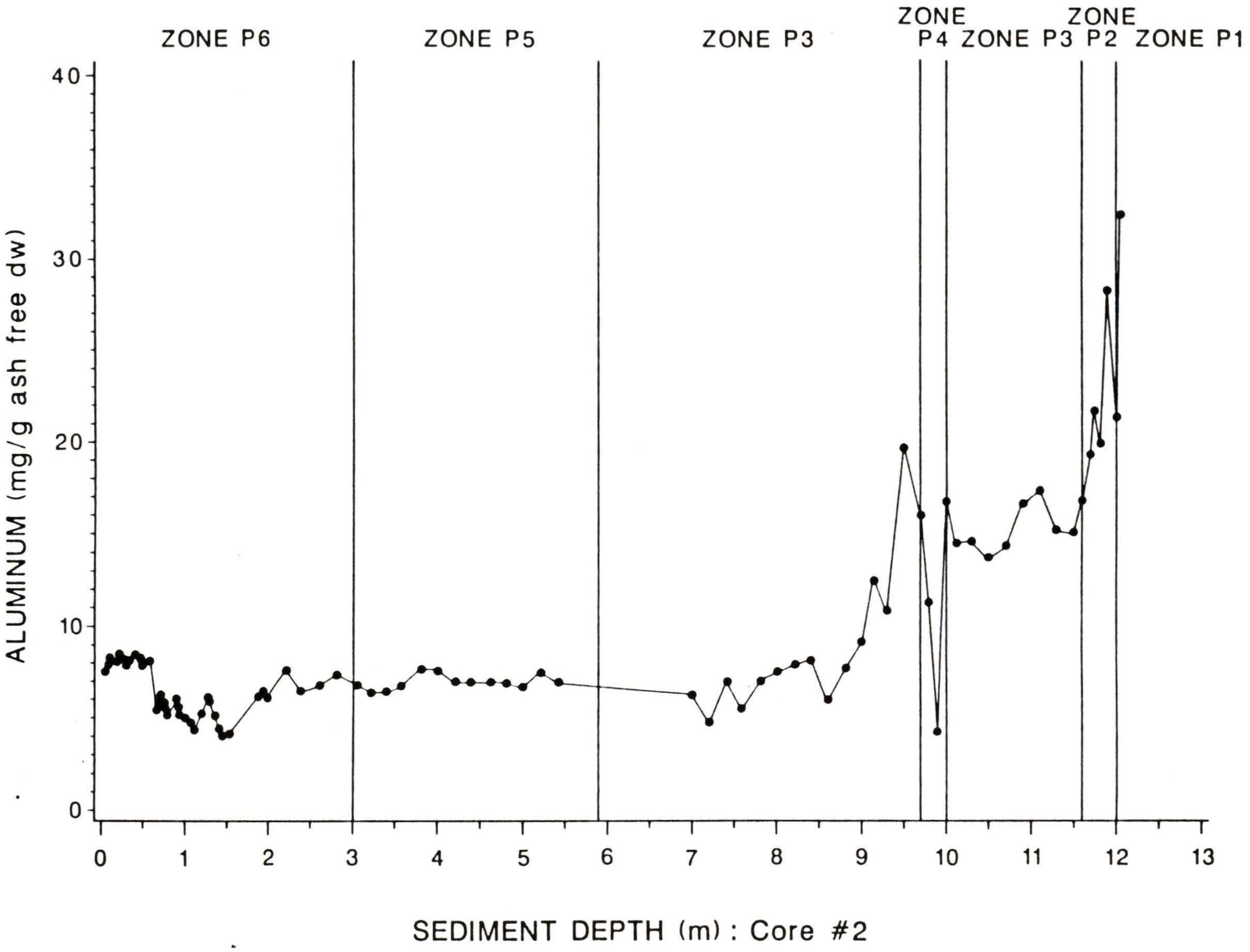

ZONE P6
ZONE P5
ZONE P3
ZONE P4
ZONE P3
ZONE P2
ZONE P1
ALUMINUM (mg/g ash free dw)
0
10
20
30
40
0
1
2
3
4
5
6
7
8
9
10
11
12
13
SEDIMENT DEPTH (m) : Core #2

Figure 23: Calcium Concentrations (mg/g ash free dw) from Core#2 as a Function of Sediment Depth for Langford Lake

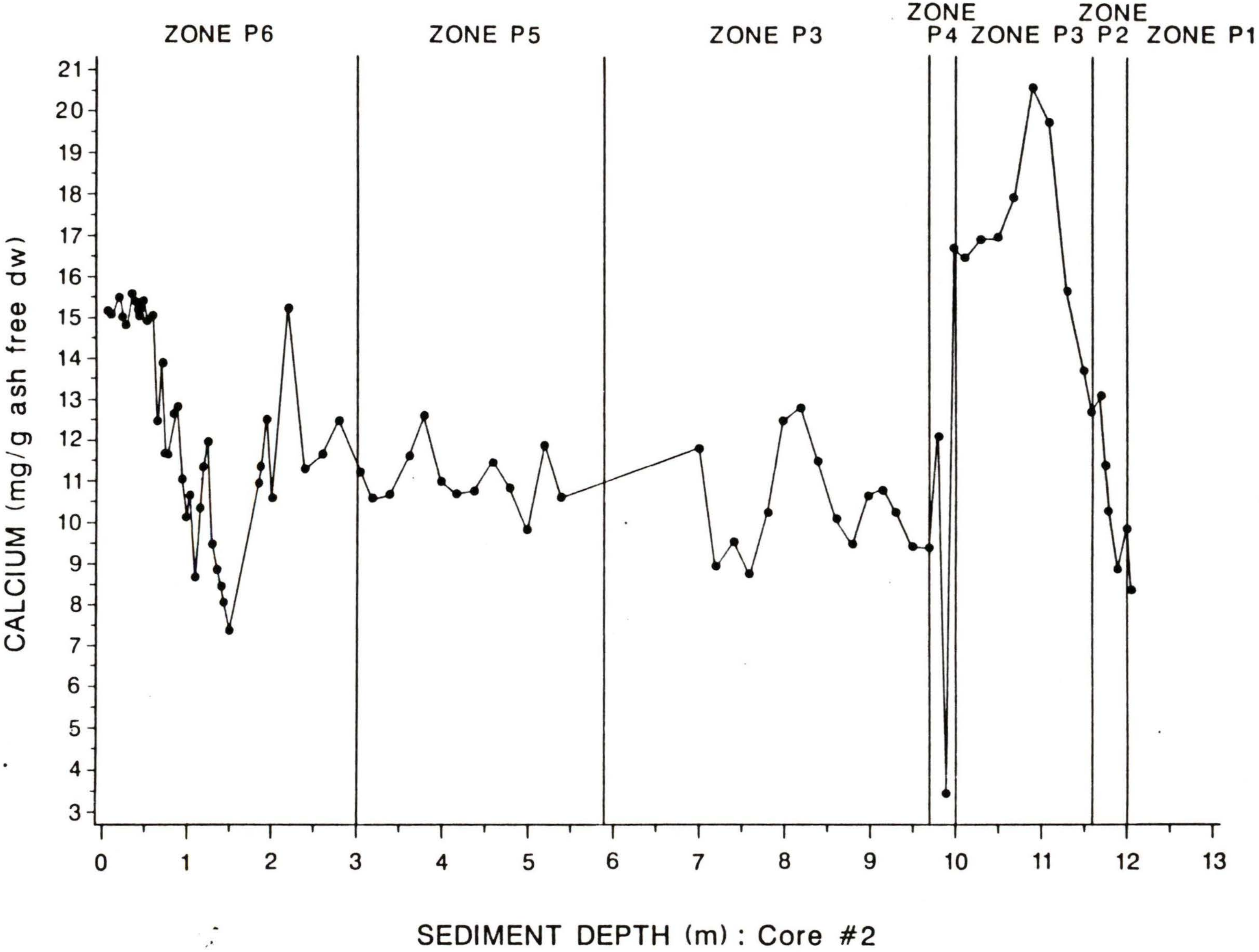

ZONE P6
ZONE P5
ZONE P3
ZONE P4
ZONE P3
ZONE P2
ZONE P1
CALCIUM (mg/g ash free dw)
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
0
1
2
3
4
5
6
7
8
9
10
11
12
13
SEDIMENT DEPTH (m) : Core #2

Figure 24: Carbon (inorganic) Concentrations (mg/g dw) from Core#2 as a Function of Sediment Depth for Langford Lake

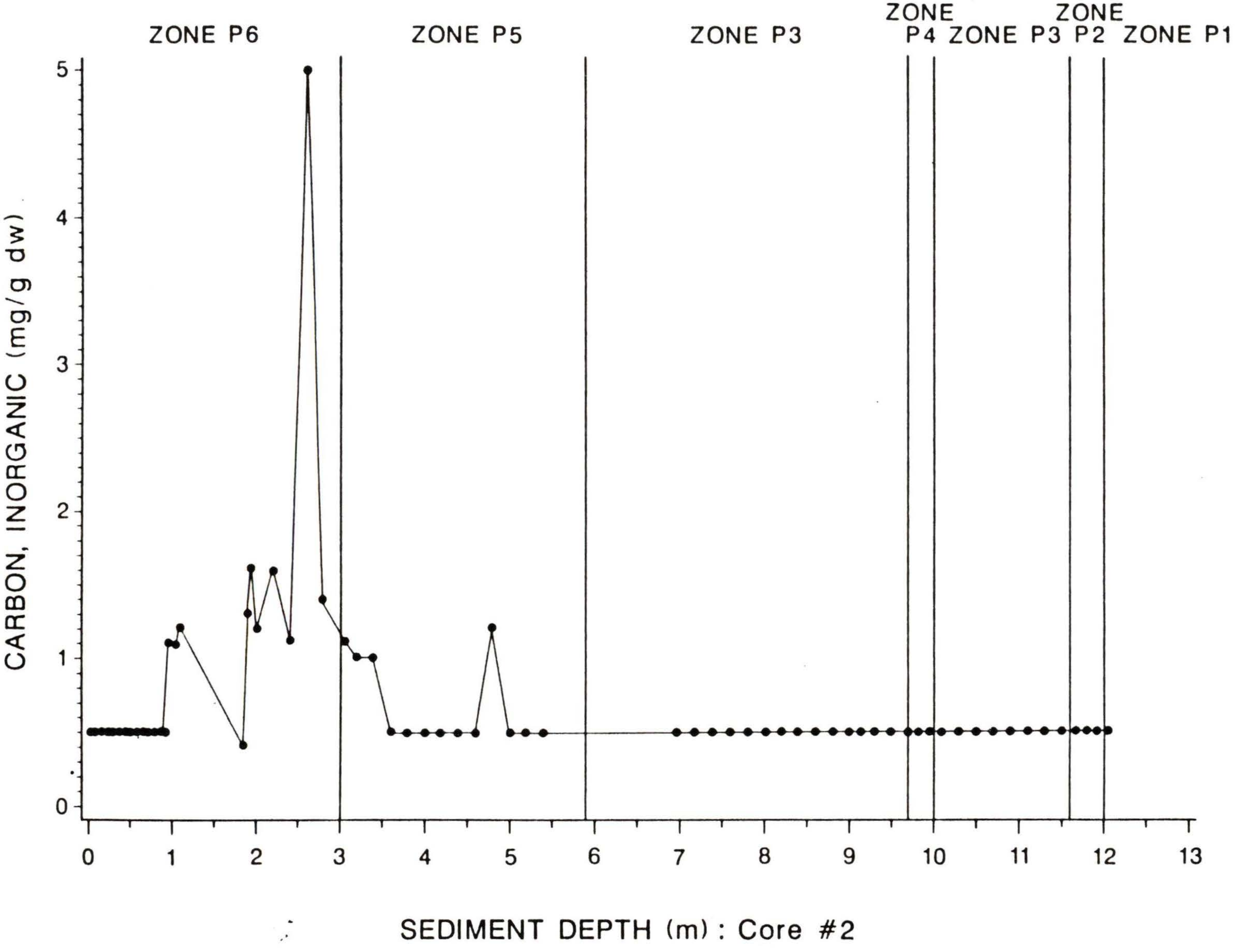

ZONE P6
ZONE P5
ZONE P3
ZONE P4
ZONE P3
ZONE P2
ZONE P1
CARBON, INORGANIC (mg/g dw)
0
1
2
3
4
5
0
1
2
3
4
5
6
7
8
9
10
11
12
13
SEDIMENT DEPTH (m) : Core #2

Figure 25: Carbon (organic) Concentrations (mg/g dw) from Core#2 as a Function of Sediment Depth for Langford Lake

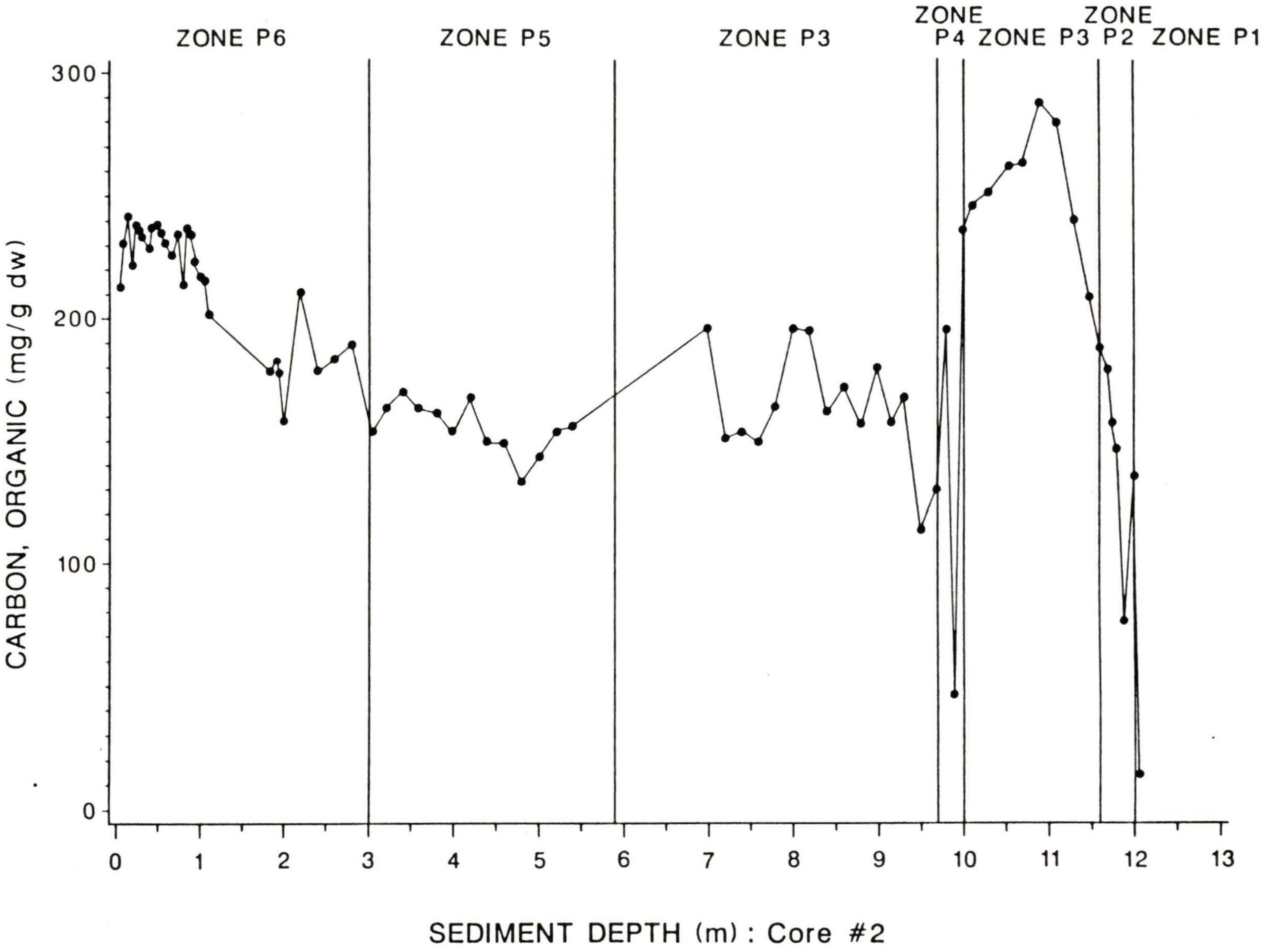

ZONE P6
ZONE P5
ZONE P3
ZONE P4
ZONE P3
ZONE P2
ZONE P1
CARBON, ORGANIC (mg/g dw)
300
200
100
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
SEDIMENT DEPTH (m) : Core #2

Figure 26: Iron Concentrations (mg/g ash free dw) from Core#2 as a Function of Sediment Depth for Langford Lake

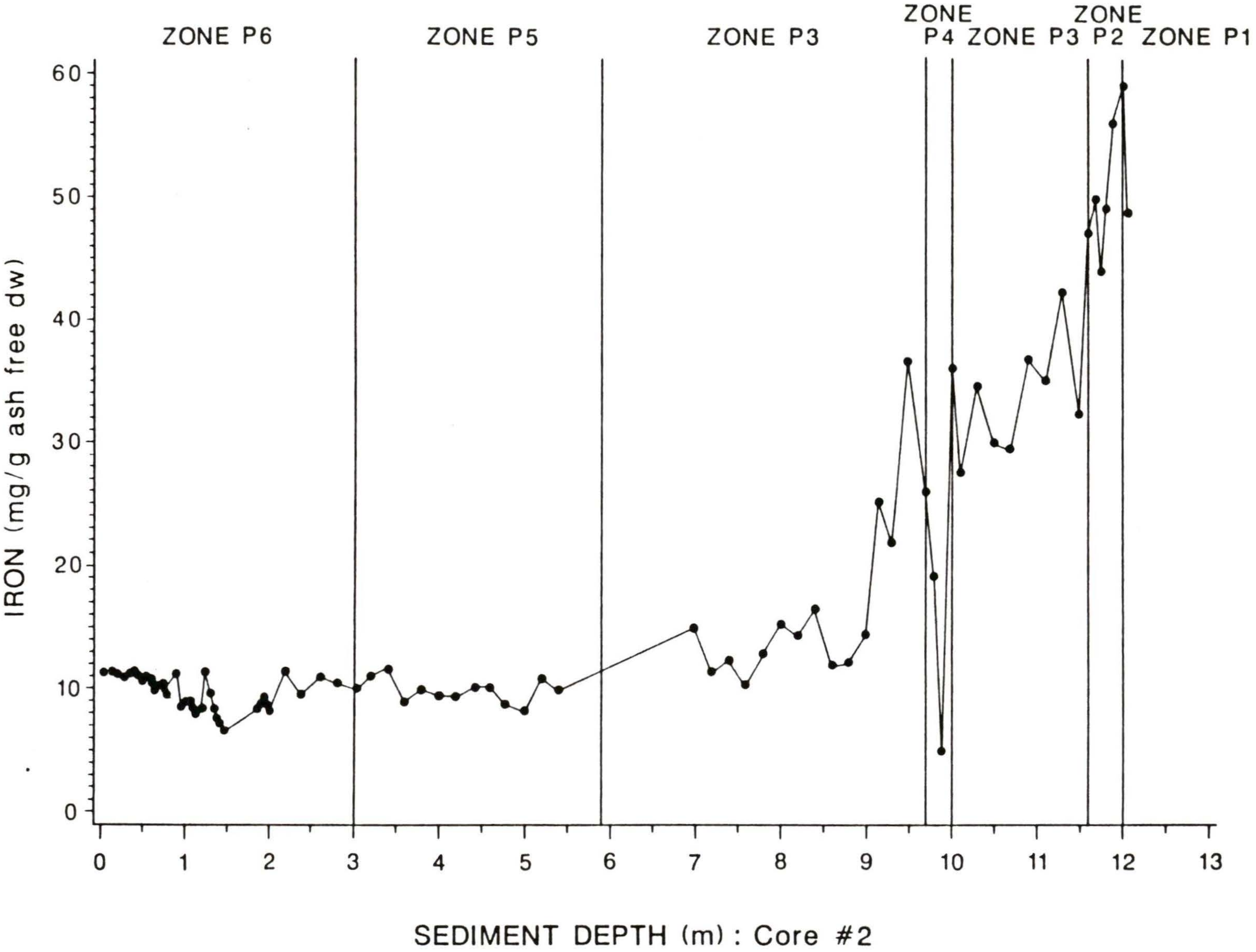

ZONE P6
ZONE P5
ZONE P3
ZONE P4
ZONE P3
ZONE P2
ZONE P1
IRON (mg/g ash free dw)
0
10
20
30
40
50
60
0
1
2
3
4
5
6
7
8
9
10
11
12
13
SEDIMENT DEPTH (m) : Core #2

Figure 27: Magnesium Concentrations (mg/g ash free dw) from Core#2 as a Function of Sediment Depth for Langford Lake

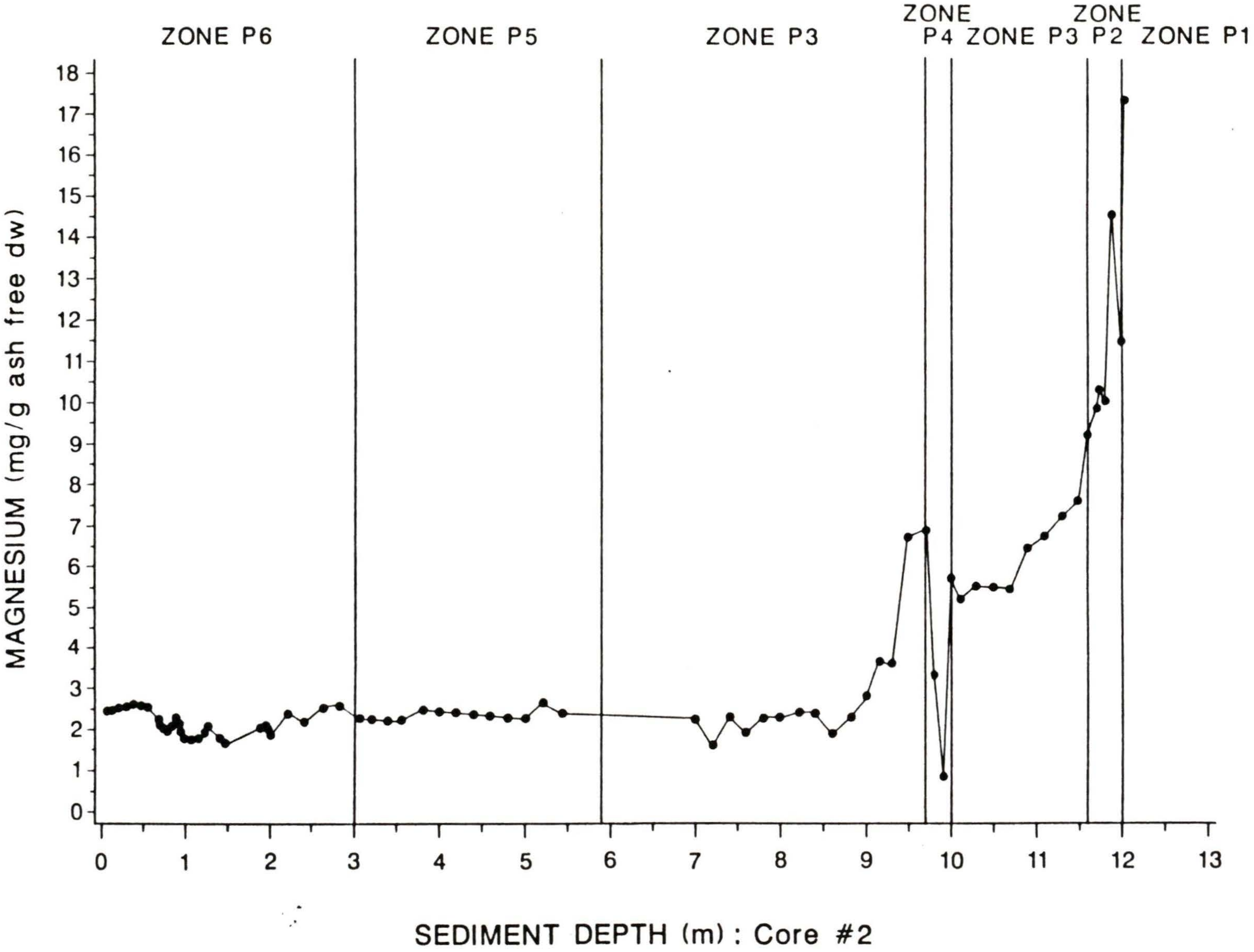

ZONE P6
ZONE P5
ZONE P3
ZONE P4
ZONE P3
ZONE P2
ZONE P1
MAGNESIUM (mg/g ash free dw)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
0
1
2
3
4
5
6
7
8
9
10
11
12
13
SEDIMENT DEPTH (m) : Core #2

Figure 28: Manganese Concentrations (µg/g ash free dw) from Core#2 as a Function of Sediment Depth for Langford Lake

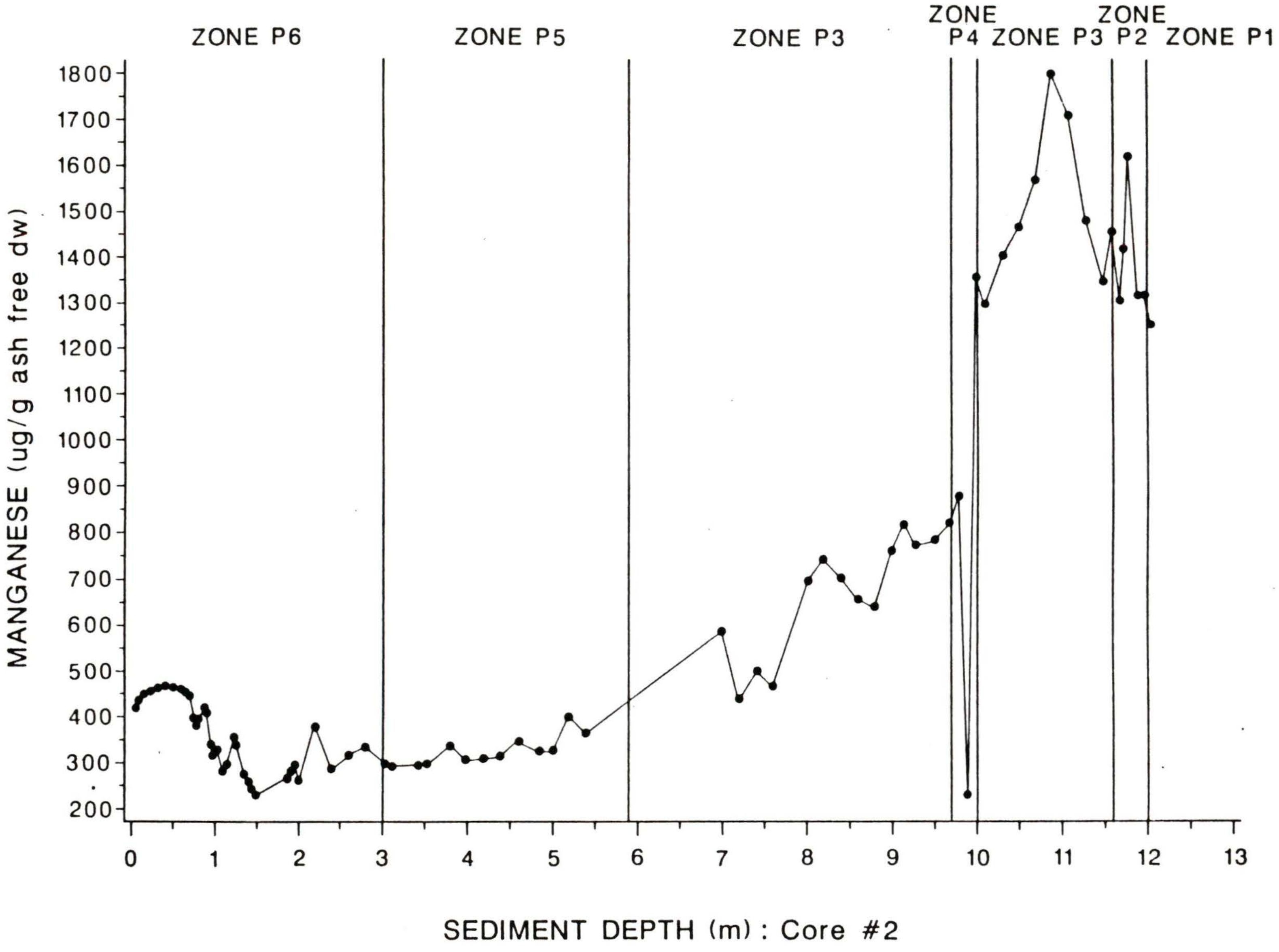

ZONE P6
ZONE P5
ZONE P3
ZONE P4
ZONE P3
ZONE P2
ZONE P1
MANGANESE (ug/g ash free dw)
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
0
1
2
3
4
5
6
7
8
9
10
11
12
13
SEDIMENT DEPTH (m) : Core #2

Figure 29: Nitrogen (Kjeldahl) Concentrations (mg/g dw) from Core#2 as a Function of Sediment Depth for Langford Lake

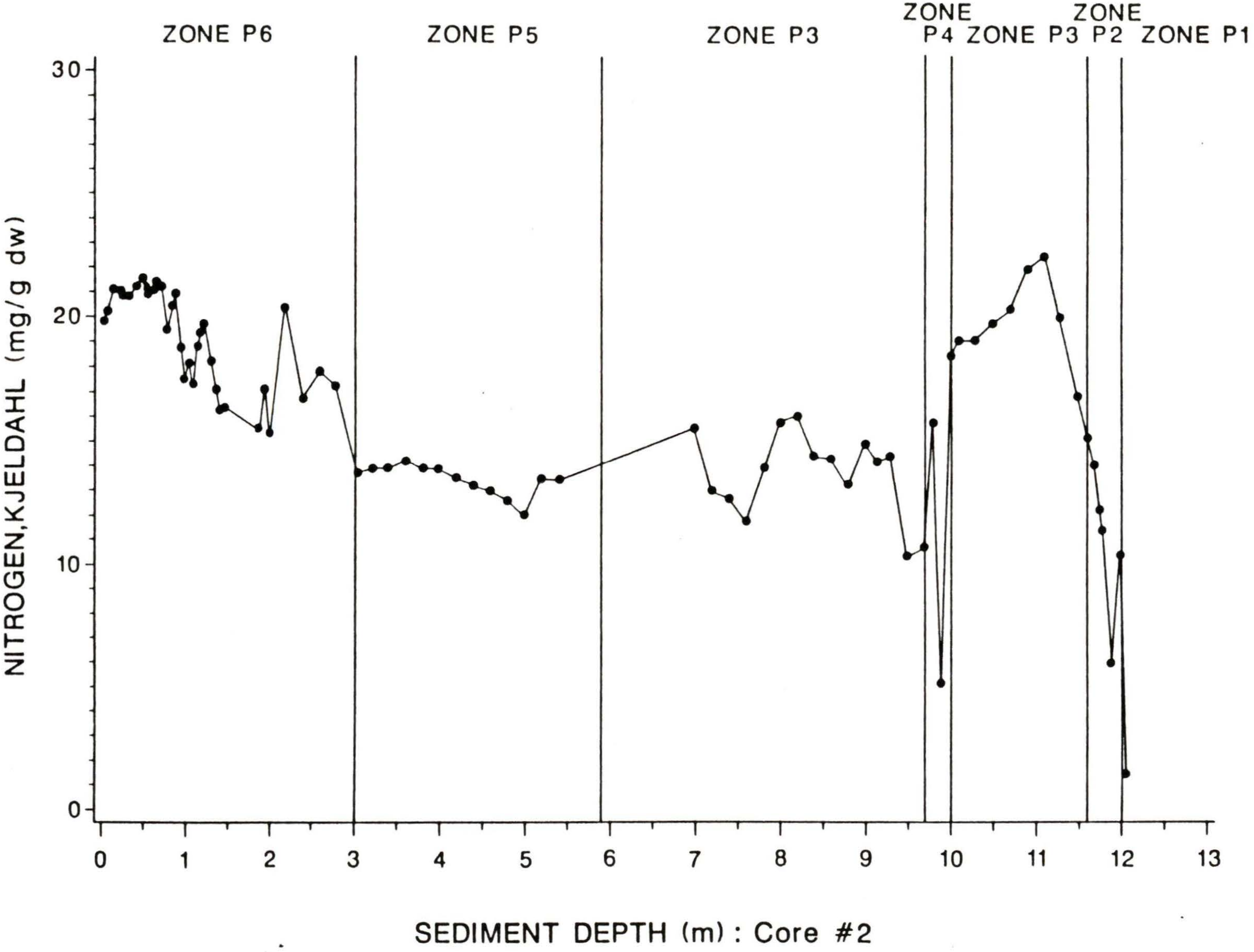
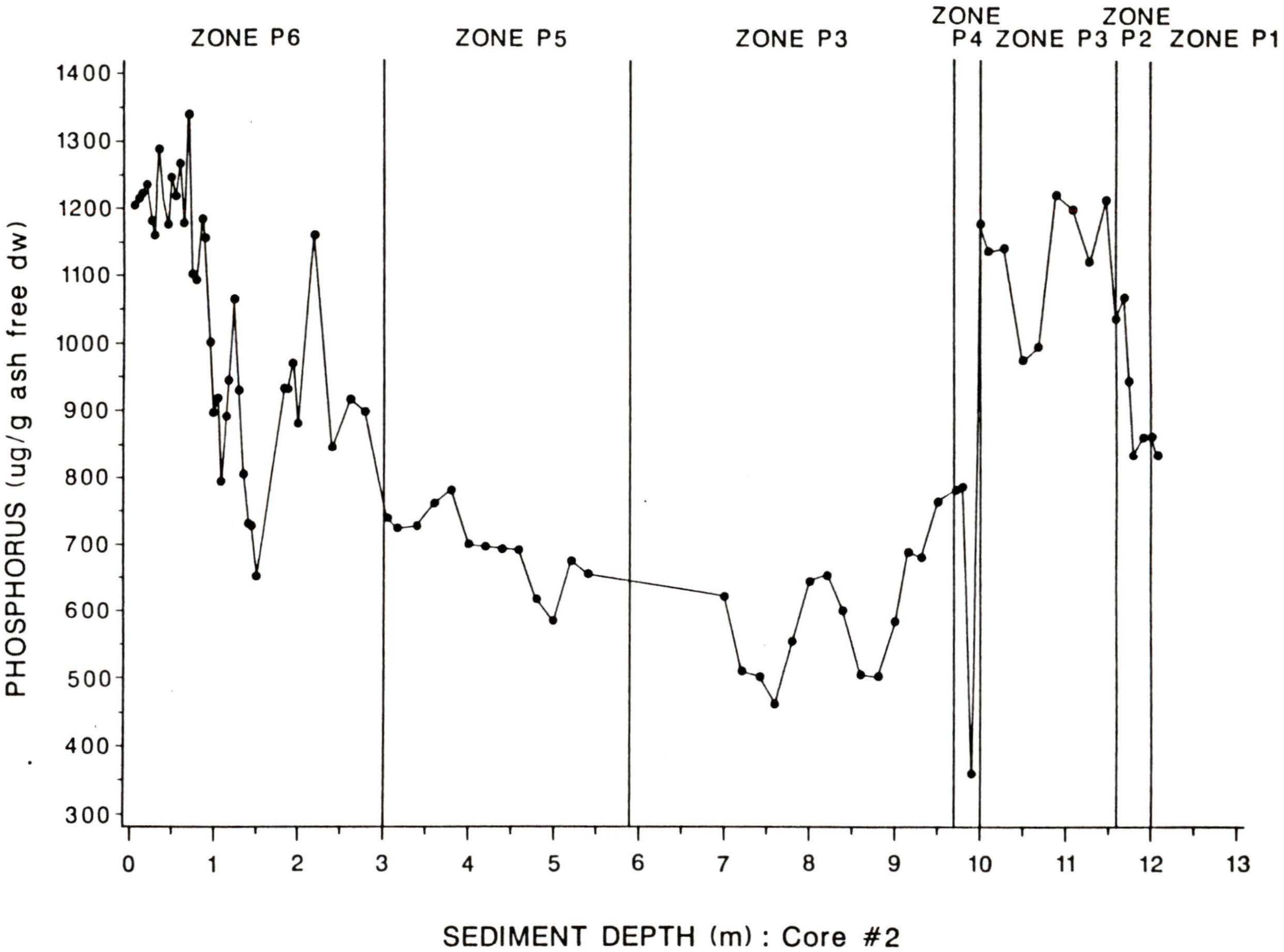

ZONE P6
ZONE P5
ZONE P3
ZONE P4
ZONE P3
ZONE P2
ZONE P1
NITROGEN,KJELDAHL (mg/g dw)
0
10
20
30
0
1
2
3
4
5
6
7
8
9
10
11
12
13
SEDIMENT DEPTH (m) : Core #2

Figure 30: Phosphorus Concentrations (μg/g ash free dw) from Core#2 as a Function of Sediment Depth for Langford Lake


ZONE P6
ZONE P5
ZONE P3
ZONE P4
ZONE P3
ZONE P2
ZONE P1
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
PHOSPHORUS (ug/g ash free dw)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
SEDIMENT DEPTH (m) : Core #2

the zone to 209 mg/g (dw) at 11.4 m (Figure 24). Metal concentrations in Zone P2 show two trends. The high aluminum and magnesium concentrations associated with the erosion of clastic minerals are not observed, however, relatively high aluminum concentrations persist within Zone P2, presumably caused by aluminum hydroxides weathered and leached from the watershed. The concentrations of iron, manganese, and phosphorus increased in Zone P2 (Figures 26, 28, and 30), because they are not associated with the clastic material, but are primarily associated with the weathering of primary and secondary minerals, and transported to Langford Lake by leaching rather than erosion.

The presence of small traces of volcanic tephra from Glacier Peak (11.76 m) did not appear to influence the concentrations of organic or inorganic constituents.

The third zone (P3) extends from 11.4 - 5.9 m, and represents the first post-glacial period. The organic carbon content of the sediments increased to a maximum at 10.9 m (287 mg/g dw), and then decreased to a plateau (175 mg/g dw), which extended from 7.4 - 6.0 m. The other elements associated with the organic fraction (calcium and Kjeldahl nitrogen) followed the same pattern. The maximum levels of calcium and Kjeldahl nitrogen of 20 mg/g ash free dw, and 22.4 mg/g (dw), repectively, were recorded in Zone P3.

Metal and phosphorus concentrations in Zone P3 showed similar trends. Concentrations of aluminum, magnesium, iron, manganese, and phosphorus declined to constant (stable?) concentrations. The base concentrations for the above elements were: Al=6.5 mg/g ash free dw; Mg= 3 mg/g ash free dw; Fe=12 mg/g ash free dw; Mn=300 µg/g ash free dw; and P= 400 µg/g ash free dw.

The fourth sediment zone (P4) reflects the impact of volcanic ash (Figure 22 - 30). The eruption of Mount Mazama (6600 BP), deposited a significant volume of volcanic ash in Langford Lake and its watershed.

The tephra is concentrated in two zones (Appendix 2), an upper zone of tephra, and a lower zone of tephra and organics. Chemical analysis of the upper zone shows a decline in all metals, organics, and phosphorus, due to the high concentrations of silicate minerals that constitute the tephra. Metal concentrations on either side of the tephra are elevated, indicating a brief period of increased metal loading associated with the weathering of the tephra.

The fifth zone (P5) occurs between 3 and 5.9 m, and is characterized by higher phosphorus concentrations (400 to 750 µg/g ash free dw, Figure 30), increasing concentrations of the organic constituents (calcium, organic carbon, and TKN, Figures 23, 25, and 29), and stable concentrations of elements that are associated with erosion and weathering of primary and secondary minerals (aluminum, iron, magnesium and manganese, Figures 22, 26, 27, and 28).

The sixth and last zone (P6, 3 - 0 m) represents the effects of watershed development on the Langford Lake sediments. The beginning of the zone is characterized by a rapid rise in Kjeldahl nitrogen, organic carbon, and phosphorus. The concentrations of the organic constituents (calcium, organic carbon, and Kjeldahl nitrogen) did not, however, increased to levels observed immediately after deglaciation (Figures 23, 25, and 29). Phosphorus concentrations did increase to levels observed immediately after deglaciation at 0.5 m. Aluminum and manganese concentrations had small increases (Figures 22 and 28), while the other metals were unchanged (Figures 26, 27, 30) in this zone.

5. DISCUSSION

5.1 Physical and Chemical Stratigraphy

The physical zones (P1-P6) described in Section 4.1 in most cases can be compared to the climatic conditions of the period. In some situations dating of the core is poor, making an association with the climatic trends difficult. Analysis of the pollen record from Core #2 will allow a thorough comparison of the physical and chemical data with the shifts in the climate and vegetation within the watershed.

Zone P1 (11.99 - 12.05 m) would be contemporaneous with the lodgepole pine-alder forest community that dominated the Vancouver Island immediately after deglaciation (Hebda, 1983). The period was cool and dry, and the soils and landforms were disturbed and unstable (Hebda, 1983). The age of the clay sediments was difficult to estimate because the ^{14}C analysis at 11.85 m was 10,670 ± 280 BP (Howes, unpubl.), while the ash of Glacier Peak, at 11.67 m, was dated at 11,300 BP (Clague, pers. comm.). The dates of Glacier Peak tephra were determined on ^{14}C results from contemporaneous wood deposits collected in the Fraser Valley. Lake sediments do not provide an accurate ^{14}C date because they have a lower carbon content (relative to terrestrial vegetation), and have been subject to vertical mixing by biota and sediment focusing (Howes, pers. comm.). Based on the presence of tephra from Glacier Peak, the bottom of the clay zone is thought to represent about 12,000 to 12,500 BP (Clague, pers. comm.).

The first zone is characterized by high rates of erosion of clastic minerals (clay) from the watershed. There are two possible sources of clay materials. The outwash stream that circumnavigated the lake (or melting ice block), or the erosion of deposited glacial materials within the watershed. Only five cm of the clay zone was collected in the corer because of the inability of the corer to penetrate the clay materials.

The elements aluminum and magnesium had high concentrations because of their association with the erosion materials (Mackereth, 1966). Autochthonous organic production would be minimal during periods of high clastic imput due to light limited conditions. The elements iron, manganese, and phosphorus have lower concentrations in the clastic materials due to the dominance of aluminosilicates (Lindsay, 1979).

The second zone (P2, 11.64 - 11.99 m) represents the transition from the dominance of clay in the first zone and the dominance of organic sediments in the third zone. The late-glacial period is dominated by the allochthonous input of eroded clastic minerals (clay), while the post-glacial period was dominated by the allochthonous input of weathered minerals, and the autochthonous production of organic matter (Limus detrituosus). This zone is thought to represent the transition from the lodgepole pine/alder community to a coastal Douglas fir/Garry oak community (Hansen, 1950). The decrease in the clastic content is evidence of the stabilization of the soils and landforms, while the presence of coastal Douglas fir/Garry oak imply a warmer climate than Zone P1.

Clague (pers. comm.) speculates that south Vancouver Island was deglaciated 12,500 BP, and the interphase between Zones P1 and P2 (12 m) would approximate that period. The presence of tephra from Glacier Peak at 11.76 m (11,300 BP, Clague et al. 1981) suggests that the bottom of Zone P2 is between 10,500 BP and 11,000 BP.

Concentrations of aluminum and magnesium decreased in this zone due to reduced clastic concentrations. Organic deposition rates of autochthonous material increased in this zone because of the absence of light limited conditions. Concentrations of iron, manganese, and phosphorus increased in this zone, and reached their highest concentrations in the Holocene record. The presence of high concentrations of metals and phosphorus (in the absence of clastic materials) indicates high rates of weathering and leaching of minerals due to the exposure of unoxidized rock surfaces created by the fracturing and grinding of rock within the glaciers.

Zone P3 (5.9 - 11.64 m) are thought to be contemporaneous with part or all of the early Holocene xerothermic interval. Garry oak and coastal Douglas fir dominated southern Vancouver Island during this period (Zirul, 1967), reflecting the warm and dry climate (Hebda, 1983). The zone is estimated to have started about 10,000 years BP, but the date is difficult to estimate because of the absence of dateable natural events (e.g. volcanic eruptions), or accurate ^{14}C results. The bottom of the zone is hypothesized to be the end of the xerothermic maximum (about 3000 years BP) based on sediment density and appearance.

The organic content reaches a maximum at the beginning of this zone, while clastics are not observed. Phosphorus, iron, and manganese concentrations declined in this zone because the rates of weathering and leaching of primary minerals from the watershed were declining. Stabilization of the watershed's soils and landforms would reduce the rate of weathering and leaching of minerals to the lake. By the end of the zone, the phosphorus, iron, and manganese sediment concentrations are constant indicating the rate of weathering of minerals had stabilized.

Zones P4 (9.9 - 9.97 m) is imbedded within Zone P3, and represents the volcanic tephra from the Mount Mazama eruption 6600 years BP (Clague, 1981). This zone is different from the preceding three zones because it was caused by a catastrophic event within the airshed, rather than changes in the watershed. The concentrations of the organic and inorganic constituents decreased in this zone because of the large quantities of volcanic tephra.

Zone P5 (3.0 - 5.9 m) is thought to represent the shift from the dry xerothermic maximum to a cooler, wetter climate (Hedba, 1983). The lack of ^{14}C data in this area of the core made the delineation of the time period difficult. The 6 m point in the core is hypothesized to be the end of the xerothermic maximum based on sediment density and appearance, while the bottom of the zone interfaces with the period of watershed development. Based on these observations, Zone P5 is thought to represent the period from 3000 to 200 years BP.

Zone P5 is characterized by increases in the organic content and phosphorus concentration. Concentrations of the elements associated with the clastic fraction (aluminum and magnesium) and the weathered fraction (iron and manganese), did not change. Increases in sediment phosphorus concentrations independent of changes in the concentrations of iron and manganese, suggest an increase in the phosphorus export coefficient from the watershed. The increase in the phosphorus export coefficient in this zone is thought to be the result of an increase in precipitation and a change in forest communities.

Woodmansee and Duncan (1980) consider the phosphorus cycle of a natural California grassland to be closed, in that very little (if any) of the phosphorus input to the system by precipitation or weathering is exported. In contrast, Dillon and Kirchner (1975) calculated a phosphorus export coefficient of 5 mg P m^{-2} yr^{-1} from the Canadian shield, Nordin and McKean (1984) estimated 6 mg P m^{-2} yr^{-1} from a coastal Douglas fir forest near Shawnigan Lake, Victoria, B.C., and Fredriksen (1979) estimated 1.8 and 6.8 mg P m^{-2} yr^{-1} from 2 coastal Douglas fir-western hemlock watersheds in Washington State. Consequently, with the shift in forest community from Garry oak to coastal Douglas fir approximately 3000 years BP (Hebda, 1983), there was a concomitant increase in the phosphorus loading to the lake, and an increase in phosphorus concentrations in the sediment. The increased phosphorus loading due to a shift in the forest communities represents an indirect effect of precipitation and climate on the limnology of Langford Lake.

The last sediment Zone P6 represents the influence of anthropomorphic development within the watershed on the lake. The zone is characterized by elevated organics, phosphorus and small increases in aluminum, iron and manganese concentrations. The concentrations of iron and magnesium did not change in Zone P6. The effects of watershed development on individual elements is discussed in Sections 5.3 - 5.10.

5.2 GENERAL CHEMICAL COMPOSITION

The proportions of organic and inorganic matter in lake sediments are a function of the relative sedimentation rates of allochthonous and autochthonous organic and inorganic fractions. The relative sedimentation rates will vary within a lake and between lakes depending on morphology, effects of wind, and the localized influence of streams and rivers. Brunskill et al. (1971) advanced a general hypothesis that the organic content of headwater lakes in the Experimental Lakes Area (ELA, Manitoba) did not imply relative autochthonous organic production (i.e. primary productivity). ELA lakes with larger watersheds, relative to the lake volume, had higher flushing rates and proportionately higher inputs of allochthonous organic matter. Consequently, lakes with higher flushing rates had higher organic sedimentation concentrations.

McKean (1986) observed the opposite trend in headwater lakes on Vancouver Island. Lakes on the island with large watersheds, mountainous relief, and high flushing rates, had higher allochthonous clastic input, due to increased erosion. Runoff on Vancouver Island can approach 3000 mm/m^2 (Water Survey of Canada, 1981), and because of the mountainous relief, the high runoff can transport more clastic materials to a lake. In contrast, lowland lakes on Vancouver Island with low watershed relief, small watersheds, and low flushing rates have high organic sediment fractions (McKean, unpubl.).

The high proportions of autochthonous organics and biogenic silica, in addition to low proportions of clastics and inorganic minerals in Langford Lake, is typical of eutrophic, lowland lakes on Vancouver Island with small watersheds and low flushing rates (McKean, unpubl.). The higher organic concentrations in the shallower areas (7-10 m), were initially thought to be associated with the more productive littoral zone or the weed beds. Distance from shore and distance from weed beds are poorly correlated with the elements associated with the organic fraction, and in all cases the correlations are not significant at the 5% level (Table 13). An alternative hypothesis to explain the negative correlations is sediment focusing. Likens and Davis (1975) first described sediment focusing in Mirror Lake. Hilton (1985) and Hilton et al. (1986) described several methods by which sediment focusing can occur, the most common of which is the physical movement of surface sediments into deeper water during fall turnover. The movement of sediment under aerobic conditions during unstratified conditions in the fall affords more time for the decomposition of the organic fraction, which produces lower concentrations with increasing water depth. Sediment cores taken from the littoral areas of Langford Lake (Hebda, unpubl.) show sedimentation rates in the littoral zone of Langford Lake to be 1/2 those recorded at the deepest part of the lake. The higher sedimentation rates in the deepest basin of Langford Lake is attributed to sediment focusing by the physical movement of sediment, which results in decreased organic concentrations.

The negative correlation between manganese and water depth is not as high at the elements associated with the organic fraction (Table 13), and its spatial distribution is somewhat irregular (Figure 23). Presumably, the manganese associated with the organic fraction would be influenced by sediment focusing, however, the solubility of the inorganic manganese minerals in the sediment is strongly influenced by redox potential (Mortimer 1941, 1942; Davison, et al., 1982). Negative redox potentials in and above the sediment-water interface would cause inorganic manganese in Langford Lake to diffuse from the sediments into the water column along a concentration gradient. McKean (1986) shows the redox potential in Langford Lake during summer stratification decreases with increasing water depth. The negative redox potentials in the deeper waters are believed to be one of the principal reasons for the lower manganese concentrations in the deeper sediments.

The influence of redox potential on manganese concentrations is supported by the observed increase in manganese following the oxidation of the sediment-water interface. Sediment manganese concentrations increased from 420 µg/g ash free dw in 1984, to 680 µg/g ash free dw in 1986 (McKean, unpubl.), following the oxygenation of the hypolimnion through the operation of a destratification aerator (Nordin and McKean, 1987).

5.3 ALUMINUM

Aluminum is one of the most abundant elements in nature, and comprises approximately 8% of the Langford Lake watershed's bedrock composition (Table 16). During weathering, aluminum is released from primary minerals (e.g. quartz, mica, feldspar, etc.) and is precipitated as a secondary mineral, primarily aluminosilicates (e.g. kaolinite, pyrophyllite, etc.). Silicon is weathered more rapidly from the aluminosilicates, leaving aluminum to oxidize and form amorphous aluminum hydroxide (Lindsay, 1979). Over time, the amorphous aluminum hydroxide will transform slowly to one or more of the crystalline minerals (e.g. gibbsite). The equilibrium reactions for various aluminum species at 25°C are given below.

	log K°
$Al_2Si_2O_5(OH)_4 + 6H^+ \rightleftharpoons 2Al^{3+} + 2H_4SiO_4 + H_2O$ aluminosilicate	5.45
$Al^{3+} + H_2O \rightleftharpoons AlOH^{2+} + H^+$	-5.02
$AlOH^{2+} + 2H_2O \rightleftharpoons Al(OH)_3 \text{ amorp.} + 2H$	-4.64
$Al(OH)_3 \text{ amorp.} \rightleftharpoons Al(OH)_3 \text{ gibbsite}$	1.62

(from Lindsay, 1979)

The Al^{3+} activity in solution is determined primarily by the amorphous aluminum fraction (Lindsay, 1979). In water, Al^{3+} is surrounded by six molecules of water forming $Al(H_2O)_6^{3+}$. As pH increases, protons are removed form the coordinated waters giving a series of hydrolysis products. For simplicity these hydrolysis species are written without showing the coordinated waters.

TABLE 16

Generalized Elemental Concentrations of the Lithosphere, the Geology of the Langford Lake Watershed, Lakes from the Coastal Douglas Fir Biogeoclimatic Zone, and the Surface Sediments of Langford Lake.

Element	Lithosphere[1]	Bedrock[2]	CDF[3]	Langford[4]
Aluminum	81.0	71.0	24.3	13.6
Calcium	36	43.2	7.1	17.5
Carbon	0	0	178	210.00
Iron	51	59.7	42.5	28.5
LOI	0	0	42	46.0
Magnesium	21.0	27.0	4.4	3.7
Manganese	0.9	1.0	0.71	0.77
Nitrogen, Kjeldahl	0.0	0	13.8	21.0
Phosphorus	1.2	1.0	2.4	1.9

- All results as mg/g ash free dry weight, except carbon and nitrogen (dw) and LOI (%)

[1] from Lindsay, 1979

[2] Average elemental content from Table 2

[3] from McKean, unpublished

[4] from Table 9, average of sites 1-34 inclusive.

$$\begin{array}{lcll}
Al^{3+} & \rightleftharpoons & Al(OH)^{2+} & + H^+ \\
Al(OH)^{2+} & \rightleftharpoons & Al(OH)_2^+ & + H^+ \\
Al(OH)_2^+ & \rightleftharpoons & Al(OH)_3 & + H^+ \\
Al(OH)_3 & \rightleftharpoons & Al(OH)_4^- & + H^+ \\
Al(OH)_4^- & \rightleftharpoons & Al(OH)_5^{2-} & + H^+
\end{array}$$

The activities of the hydrolysis species are plotted as a function of pH in Figure 31. The activity of aluminum ions increases when the pH decreased below pH 5.8, or increases above pH 8.2.

The principal aluminum ions in Langford Lake, based on an average pH of 7.4 (Table 6), will be $Al(OH)_3^0$ and $Al(OH)_4^-$. The interstitial pH of the sediments is lower than that of the overlying water (pH ~ 6.5; McKean, 1986), indicating that $Al(OH)_3^0$ would be the primary interstitial aluminum species (Figure 31).

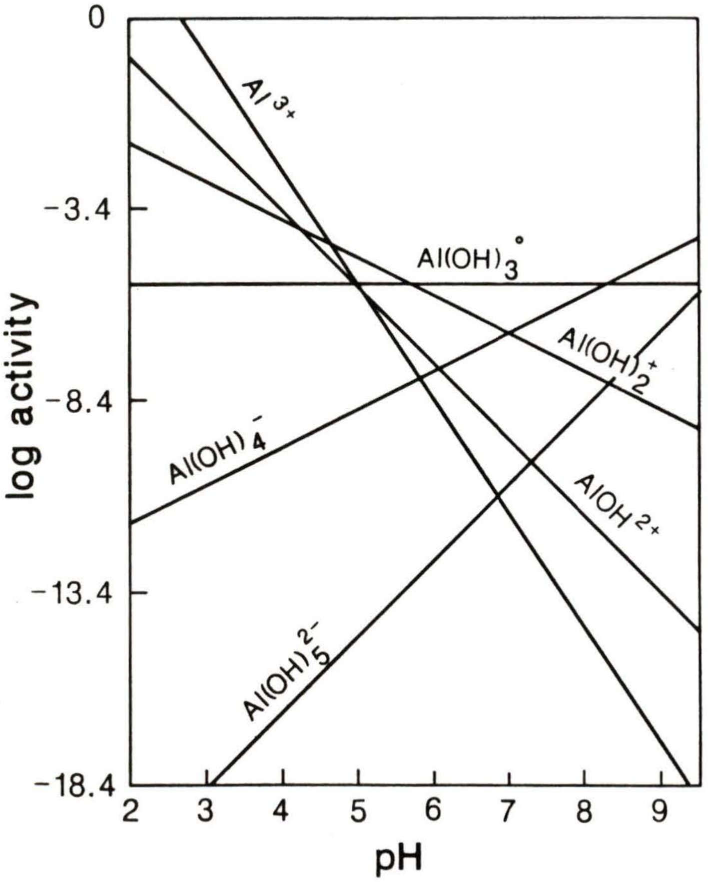
The formation of aluminum-phosphates (variscite: $AlPO_4 \bullet 2H_2O$) can be an important mechanism for binding phosphorus in lake sediments. Aluminum sulphate has been successfully added to lakes to bind orthophosphate in the sediments (Narf, 1985). The formation of variscite (equation below) is quite stable, and unlike iron-phosphates (strengite), the solubility of variscite is not influenced by redox potential.

$$Al^{3+} + H^+ + H_2PO_4^- + 2H_2O \rightleftharpoons AlPO_4 \bullet 2H_2O + 3H^+$$

log K° = 2.5 (from Lindsay, 1979).

The importance of variscite in binding orthophosphate depends on the

Figure 31: The Activity of Al^{3+} and its Hydrolysis Species as a Function of pH (from Lindsay, 1979).


0
-3.4
-8.4
-13.4
-18.4
log activity
2
3
4
5
6
7
8
9
pH
Al 3+
Al(OH)3°
Al(OH)2+
Al(OH)4-
AlOH 2+
Al(OH)5 2-

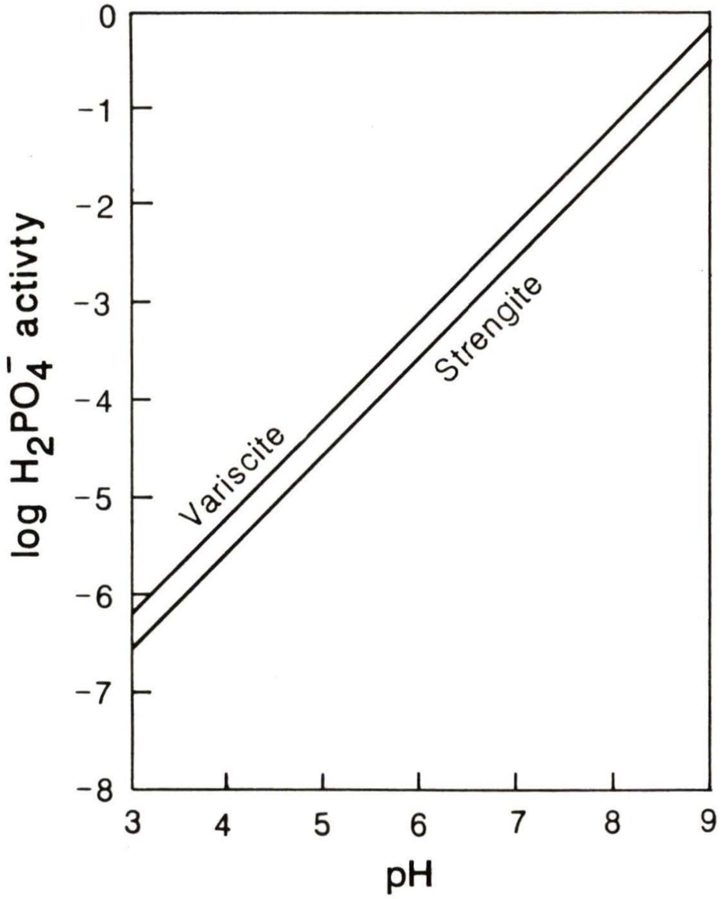
activity of Al^{3+}, which in turn is determined by the concentration of $Al(OH)_3$ (amorp.) in the sediment and the interstitial pH. The activity of orthophosphate increased 10-fold for every unit increase in pH, reflecting the concomitant reduction in Al^{3+} activity (Figure 31), and the solubility of aluminum minerals (Figure 32). The importance of variscite as compared to iron-phosphates is discussed in Section 5.6.

The concentration of aluminum in the surface sediments averaged 13.6 mg/g or 0.0005 moles/g ash free dw (Table 16). Based on molarity, aluminum was the third most common element associated with Langford Lake's inorganic sediments, and had a similar concentration to that in the bedrock (Table 16).

Lindsay (1979) observed the precipitation of amorphous aluminum hydroxide ($Al(OH)_3$) in soils, with the formation of more structured minerals (e.g. gibbsite) over time. Based on the results of the differential extraction procedures completed at the Kelowna Soils Laboratory (McKean, unpubl.), the amorphorus aluminum content of the surface sediments of Langford Lake respresents 80% of the total mineral fraction, and 60% of the total aluminum fraction. The remainder of the aluminum is associated with the organic fraction (20%) and the inorganic crystalline minerals (20%). The proportion of crystalline aluminum minerals is expected to increase with increasing sediment depth due to the transformation of amorphous aluminum over time.

The concentration of aluminum in the surface sediments of Langford Lake was negatively correlated with water depth ($r= ^{-}0.60$, $n=34$), but the highest concentrations were recorded near the shores (Figure 10), which suggested that the erosion from the littoral zone (wave action zone) was an important source of aluminum in Langford Lake. The association of aluminum with erosion is demonstrated in the core data. Aluminum concentrations within Zone P1 is 3 to 4 times higher than the present day concentrations because of the high rates of erosion of aluminosilicate minerals (Figure 22). The presence of aluminum in

Figure 32: The Solubility of Varisite and Strengite as a Function of pH (modified from Lindsay, 1979).


0
-1
-2
-3
-4
-5
-6
-7
-8
log $H_2PO_4^-$ activty
3
4
5
6
7
8
9
pH
Variscite
Strengite

the other zones suggests aluminum is also present as amorphous aluminum hydroxide, produced within the watershed by the process of weathering, and transported to the lake by leaching.

The concentration of amorphous aluminum in Fontana Lake (North Carolina, USA) is elevated near its sources, a series of inflow rivers draining a pristine park (Abernathy _et al_., 1984). The inflows of Langford Lake are much smaller in comparison, and did not influence the distribution of aluminum; however, based on the distribution of aluminum in Figure 18, the erosion shores to the south and east are major sources of aluminum in the lake. Sly (1976) observed elevated aluminosilicates with increasing water depth in the Great Lakes. The increase is in response to decreasing water energies and increasing clay deposits. Kemp _et al_. (1976), and Kemp and Thomas (1976), however, did not observe any increase in total aluminum concentrations in the recent sediments from Lake Erie and Lake Huron. They described aluminum to be a conservative element in large lakes.

The eruption of Mount Mazama briefly increased the aluminum content of the sediments through its association with the tephra. Following the Mount Mazama eruption, the aluminum concentrations remained relatively constant (6-7 mg/g ash free dw) until the effects of watershed development are observed in the modern sediments. Two responses are observed, decreased aluminum concentrations presumably due to the construction of the railway and the diversion of runoff from the southern portion of the watershed, and second increased aluminum concentrations presumably due to the exposure and erosion of soils and landforms from watershed development. Mathews and D'Auria (1982) noted an aluminosilicate peak in Deer Lake (a small urban watershed near Vancouver, Canada) because of an increase in erosion of clay particles following watershed development.

5.4 CALCIUM

The calcium content of the bedrock in the Langford Lake watershed is variable (0.8 - 10.4%; Table 2), but averaged 43 mg/g ash free dw (Table 16). The average surface calcium concentration of the lake sediments is much less (17.5 mg/g ash free dw, Table 9), indicating a portion of the calcium remains in solution.

The calcium content of soils is largely determined by the composition of the parent material and rainfall. If rainfall is sufficient to leach the calcium as it is weathered, calcium minerals will be depleted from the soils. If, however, the rainfall is not sufficient to leach all the weathered calcium, the interstitial calcium concentrations will increase and eventually precipitate primarily as calcium carbonate, and accumulate in the soil (Lindsay, 1979).

The weathering reactions of primary calcium minerals (e.g. calcium silicates) and secondary minerals (e.g. calcium-aluminosilicates) are summarized below.

$$\beta CaSiO_3 + 2H^+ + H_2O \rightleftarrows \underset{\text{(wollastonite)}}{Ca^{2+} + H_4SiO_4^{o}}$$

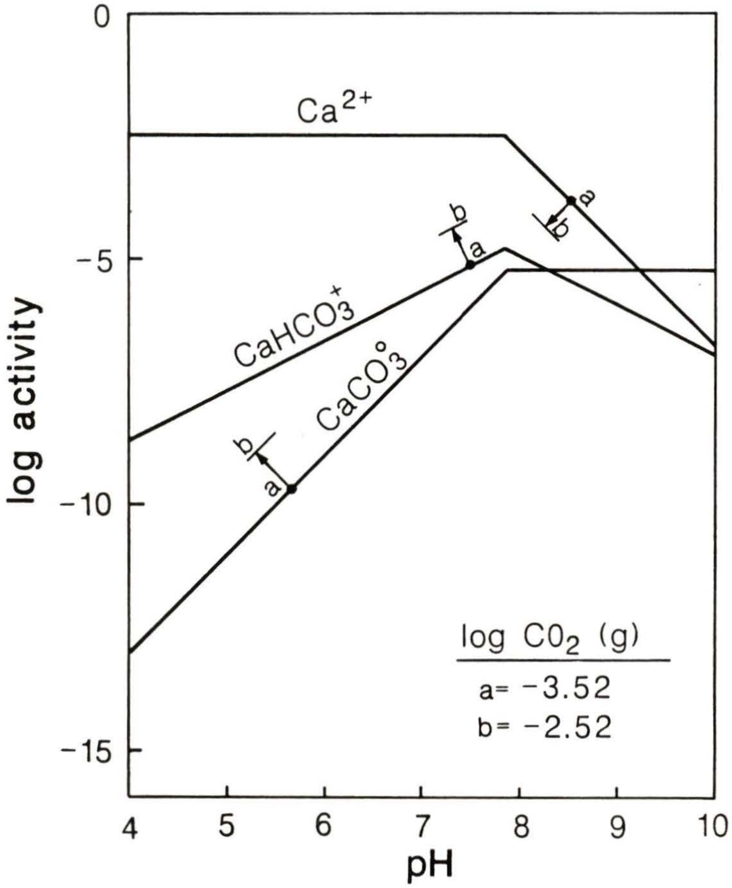
$$\log K^{\circ} = 13.27$$

$$\underset{\text{(wair)}}{CaAl_2Si_4O_{12}\ 2H_2O} + 2H^+ \rightleftarrows Ca^{2+} + \underset{\text{(kaolinite)}}{Al_2Si_2O_5(OH)_4} + \underset{\text{(quartz)}}{2SiO_2} + H_2O$$

$\log K^{\circ} = 18.60$ (from Lindsay, 1979).

The solubility of the calcium ion (Ca^{2+}), calcium bicarbonate, and calcium carbonate in water is summarized in Figure 33. Ca^{2+} is the most common calcium ion with a maximum activity of $10^{-2.5}$ moles/L

Figure 33: The Effects of pH on the Activities of the Calcium Ion, and Carbonate Complexes of Ca^{2+} in Equilibrium with Calcite (from Lindsay, 1979).


0
-5
-10
-15
log activity
4
5
6
7
8
9
10
pH
Ca2+
CaHCO3+
CaCO3°
a
b
log CO2 (g)
a= -3.52
b= -2.52

(126.7 mg/L), when in equilibrium with calcium carbonate at a pH less than 7.8. An increase in pH or $CO_{2(g)}$ activity results in a decrease in the activity of Ca^{2+} (Figure 35), because of the inactivation of Ca^{2+} ions by carbonates. The concentration of calcium in British Columbia lakes ranges from 0.3 to 2030 mg/L (Warrington, unpubl.), but in lakes where inorganic carbon is the dominant anion, calcium concentrations do not exceed 50 mg/L, due to the precipitation of calcium carbonate.

The high equilibrium constants (log K°) for the production of Ca^{2+} ions (relative to other elements) from primary and secondary calcium minerals, combined with the high solubility of the Ca^{2+} ion, are the principal reasons why calcium is the dominant cation in Langford Lake (Table 3), the lakes within the Coastal Douglas Fir Biogeoclimatic Zone (McKean, unpubl.), and the lakes of British Columbia in general (Warrington, unpubl.).

Calcium in lake sediments can be formed from biotic or abiotic sources. Calcium minerals are important building components of invertebrate exoskeletons (insect + crustacean chitin, mollusc shells, etc.) and vertebrate bone. Calcium from abiotic sources can also occur in sediments through the erosion of unweathered calcium minerals (e.g. calcium silicates, calcite, etc.) from the watershed, or through the precipitation of calcium salts. In non-arid areas, the leaching of the highly soluble calcium ions will exceed the rate of weathering of calcium from primary and secondary minerals. In arid areas the weathering of calcium will exceed leaching, and the dissolved calcium (in association with inorganic carbon; see Section 5.5a), will precipitate primarily as calcium carbonate.

The formation of calcium carbonate (marl) is not evident in the Holocene sediments of Langford Lake. The warm dry conditions of the early Holocene xerothermic maximum caused marl formation to occur in Lake Isle, Alberta (Hickman and Klarer, 1981), and Finney Lake near

Hat Creek, British Columbia (Hebda, unpubl.), but the climatic conditions were not sufficiently arid on the coast to cause marl formation in Langford Lake.

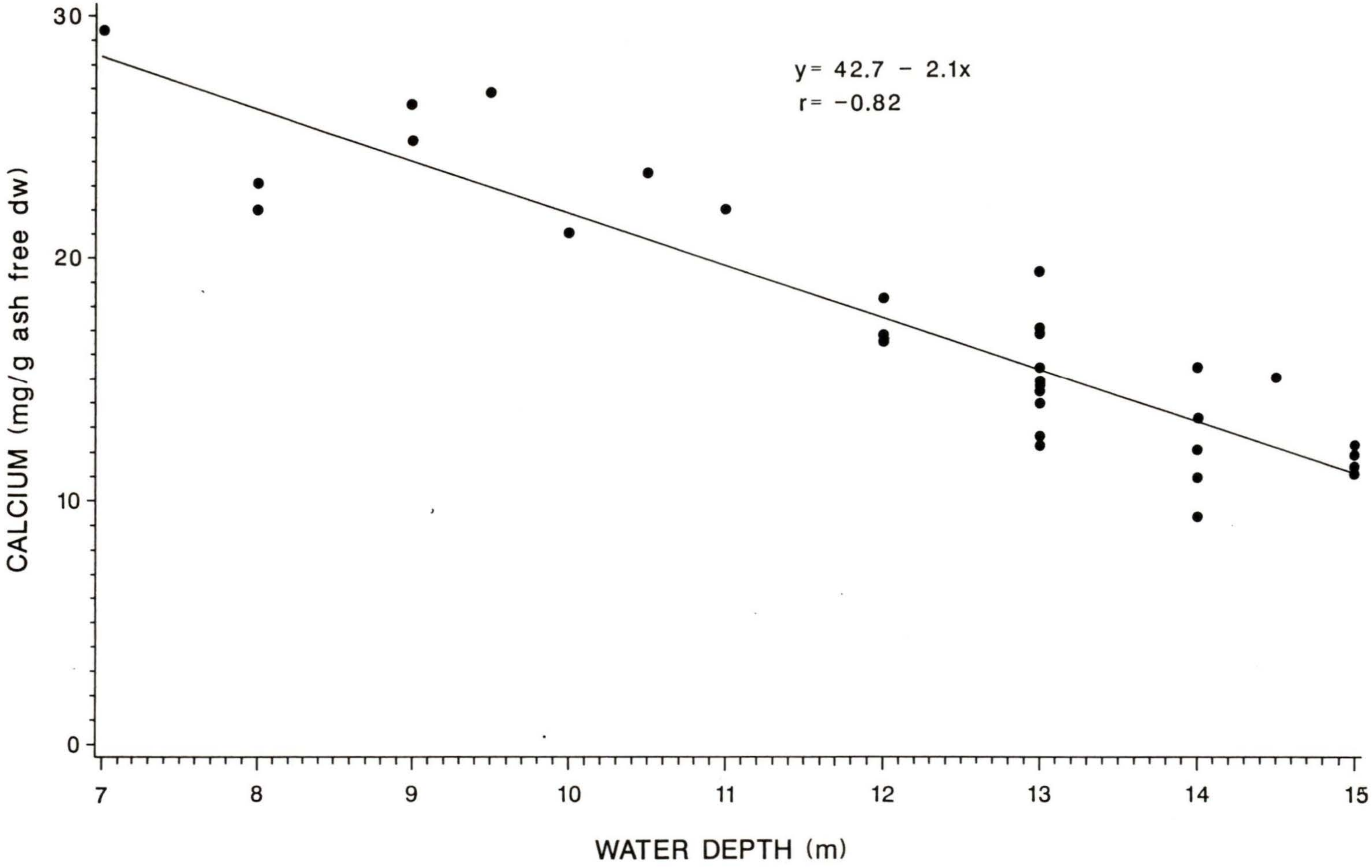
The mean concentration of calcium in the surface sediments of Langford Lake is less than half the average calcium content of the local bedrock geology around the lake (Table 6). The reason for the difference appears to be the solubility of inorganic calcium in water and the association of calcium with the sediment organic fraction.

Calcium is highly correlated with organic carbon, and TKN, indicating that the element is incorporated in the organic component, and is of a biogenic origin. The surface concentrations of calcium are correlated with water depth ($r={}^{-}0.89$) accounting for 79% ($r^2 = 0.79$) of the observed within-lake variability (Figure 34). The decrease in calcium concentrations with water depth was attributed to the increased decomposition of organic matter in the deeper parts of the lake (Section 5.5b).

The vertical distribution of calcium is also correlated with the organic fraction (Table 15). The highest calcium concentrations in Langford Lake are recorded immediately after deglaciation (Zone C2), and are the result of higher rates of autochthonous organic production and sedimentation (see Section 5.5b).

The sediment studies at Ennerdale Water (English Lakes District, Mackereth, 1966), Loch Sionascraig (Scotland, Pennington et al., 1972), and the lakes of northern Minnesota (Dean and Gorham, 1976) provide comparison with the calcium data from Langford Lake. The lakes from these studies are comparable to Langford Lake because they are located within the north temperate climatic region, have igneous bedrock geologies, and the analytical methods used are similar. Although there are significant calcium concentrations (typically 60-80 mg/g) in igneous rock (primarily as calcium silicates), calcium carbonate was

Figure 34: Surface Sediment Calcium Concentrations (mg/g ash free dw) as a Function of Water Depth in Langford Lake


y= 42.7 - 2.1x
r= -0.82
CALCIUM (mg/g ash free dw)
30
20
10
0
7
8
9
10
11
12
13
14
15
WATER DEPTH (m)

not detected in the sediments of any of the above lakes.

The vertical distribution of calcium in Ennerdale Water is similar to Langford Lake for two reasons. First the sediment calcium is correlated with organic carbon, and second, the input of clastic materials is minimal (See Section 5.5b). The vertical distribution of calcium in Loch Sionascraig, on the other hand, did not exhibit a similar calcium (or carbon) pattern because the variable influx of clastic materials masked any patterns of the organic fraction (Pennington *et al*., 1972).

5.5 CARBON

Carbon can be present in water and sediments as inorganic carbonates and organic proteins, carbohydrates, etc. The processes by which inorganic and organic carbon precipitate as sediment are independent and are discussed separately.

a) Inorganic Carbon

The inorganic carbon fractions in water are $CO_{2(g)}$, carbonic acid ($H_2CO_3^{\circ}$), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}), which are in equilibrium with each other through the following reactions.

$$CO_{2(g)} + H_2O \rightleftarrows H_2CO_3^{\circ} \qquad \log K^{\circ} = {}^{-}1.46$$

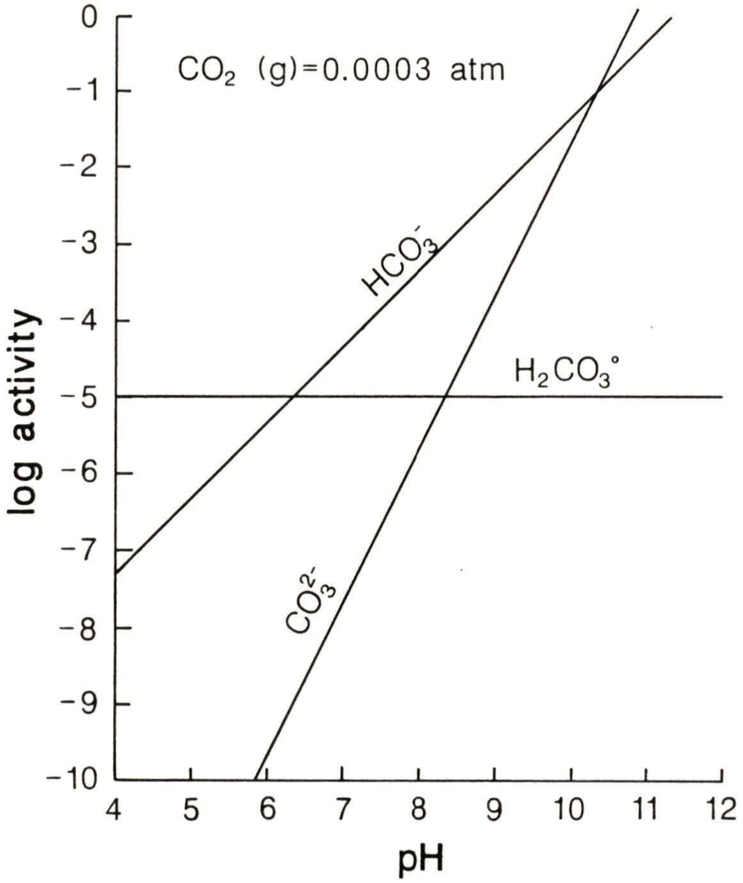
$$H_2CO_3^{\circ} \rightleftarrows H^+ + HCO_3^- \qquad \log K^{\circ} = {}^{-}6.36$$

$$HCO_3^- \rightleftarrows H^+ + CO_3^{2-} \qquad \log K^{\circ} = {}^{-}10.33$$

(from Lindsay, 1979)

The activities of the various inorganic carbon components, as a function of pH, are given in Figure 35. The activity of carbonic acid is $10^{-4.98}$ moles (0.011 mg/L) and is independent of pH. The activities of bicarbonate and carbonate increase 10 and 100 fold,

Figure 35: The Effect of pH on the Activities of Carbonate Species in Equilibrium with CO_2 (from Lindsay, 1979)


CO_2 (g)=0.0003 atm
HCO_3^-
$H_2CO_3^\circ$
CO_3^{2-}
log activity
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
4
5
6
7
8
9
10
11
12
pH

respectively, for each unit increase in pH.

The inorganic carbon content and theoretical pH of pure water in equilibrium with atmospheric CO_2 (0.0003 atm) are approximately $10^{-4.93}$ moles and 5.6, respectively (Lindsay, 1979). Inorganic carbon concentrations increase in fresh water environments by the weathering of primary and secondary minerals (e.g. calcium silicates, aluminosilicates, etc.). The following equation is used as an example.

$$Al_2Si_2O_5(OH)_4 + 6H^+ \rightleftharpoons 2Al^{3+} + 2H_4SiO_4^{\circ} + H_2O$$

(from Lindsay, 1979)

In pure water, the H^+ ions required for the weathering process come from the dissociation of carbonic acid, which produces H^+ and HCO_3^- (bicarbonate). Because the activity of $H_2CO_3^{\circ}$ is in equilibrium with $CO_{2(g)}$, carbonic acid will be replenished from the pool of $CO_{2(g)}$ (primarily atmospheric) (Bohn et al., 1979). The concentration of bicarbonate (and subsequently carbonate) in water will be determined by the amount of weathering of the surrounding soil or bedrock, which is a function of contact time, and the reactivity of the soil or bedrock. In arid areas where the weathering of secondary minerals exceeds leaching, due to low precipitation, the soils and groundwater become saturated with carbonates (Bohn et al., 1979). Carbonates will precipitate in lakes when their concentrations exceed the saturation point of a carbonate mineral (primarily calcium carbonate). Calcium carbonate (marl) precipitation usually occurs in the summer because the saturation point of calcium carbonate decreases with increasing water temperature, and algal photosynthesis increases the pH, and molar ratio of carbonate and bicarbonates (Murphy et al., 1985; Wetzel, 1983).

The concentration of inorganic carbon in the Langford Lake sediments is below the 0.5 mg/g (dw) detection levels in the surface sediments and throughtout most of the vertical stratigraphy (Figure 24). A small peak was observed between 2 and 3 m and may have been caused by the agricultural application of lime. Except for the anthropomorphic sources of inorganic carbon the climatic conditions are not sufficiently arid to allow for the accumulation of carbonates in the soil and water. The warm dry early Holocene xerothermic interval (Zone P3) was a period when the dissolved inorganic concentrations in Langford Lake would have been higher, but the period was not sufficiently arid to create the conditions that cause marl formation.

b) Organic Carbon

Organic carbon is produced by terrestrial (allochthonous) and aquatic (autochthonous) autotrophs through the process of photosynthesis. The basic requirements for the reaction are light, inorganic carbon, and water, in association with plant pigments. The sugars produced by photosynthesis are the source of energy or the basic component of a variety of organic compounds required for plant growth and reproduction. The volume of inorganic carbon consumed by an autotroph or a population of autotrophs is a measure of primary production.

The rate of autochthonous primary production is primarily limited by the availability of phosphorus (Vollenweider, 1968; Schindler, 1974, and others), but it is also influenced by lake morphology (Rawson, 1956), and light (Wetzel, 1983). Although primary production can also be limited by nitrogen (Forsberg and Ryding, 1980), iron (Murphy, et al. 1983) and other micronutrients, the majority of lakes in British Columbia are limited by phosphorus (Nordin and McKean, 1984).

In lakes, the organic carbon production ranges from <50 mg C m^{-2} day^{-1} in ultraoligotrophic lakes (spring overturn phosphorus <5 $\mu g/L$; Wetzel, 1983), to >1000 mg C $m^{-2} day^{-1}$ in eutrophic lakes (spring overturn phosphorus >30 μg/L; Wetzel, 1983). The primary source of inorganic carbon for the terrestrial and aquatic plants is ultimately atmospheric carbon dioxide. This is a major distinction from the other inorganic elements in lake sediments, which are derived from the erosion or weathering of bedrock or soils within the watershed.

Decomposition represents the processes that break down organic compounds, and it can occur under aerobic or anaerobic conditions by micro- or macro-heterotrophs in the water column or sediments. Depending on the environmental conditions (temperature, dissolved oxygen, substrate, etc.), the decomposition rates and products (CO_2, dissolved organic carbon, methane) are quite different. The decomposition rates of dead algal cells are 25% lower under anaerobic conditions then in aerobic conditions (Wetzel, 1983).

Deevey (1955) postulated that the higher rates of organic accumulation in the deepest zones of the lake are the result of incomplete anaerobic decomposition. This phenomenon is now known to be caused by the physical movement of sediments through the process of sediment focusing (Likens and Davis, 1975), rather than differential rates of decomposition.

Andersen and Jacobsen (1979) noted 82% of the decomposition of organic carbon took place in the water column, 18% in the sediment, and that 2% of the gross primary productivity was permanently retained in the sediment. They also noted that 10% of the sediment decomposition is attributed to macrobenthos. Kerr et al. (1973) noted that the decomposition of organic matter in the water column varied depending on the length of time the organics remained dissolved or suspended, which in turn was determined by water depth and degree of turbulence.

The rates of organic sediment decomposition are strongly influenced by the environment (temperature, DO, etc.), but in most circumstances the sediments contain refractive organic materials that are relatively resistant to further bacterial decomposition (Kemp and Lewis, 1968; Schindler and Alberts, 1975; Wetzel, 1983). However, under favourable environmental conditions (oxygen & temperature), additional decomposition is possible. Organic carbon concentration of surface sediments at site 1 (Figure 9) decreased approximately 10% following the installation of a destratification aerator in 1984 (McKean, unpubl.). Organic carbon concentrations decreased 20 mg/g (dw) to 165 mg/g (dw) at the deepest point in the lake in August, 1985, following two years of aeration.

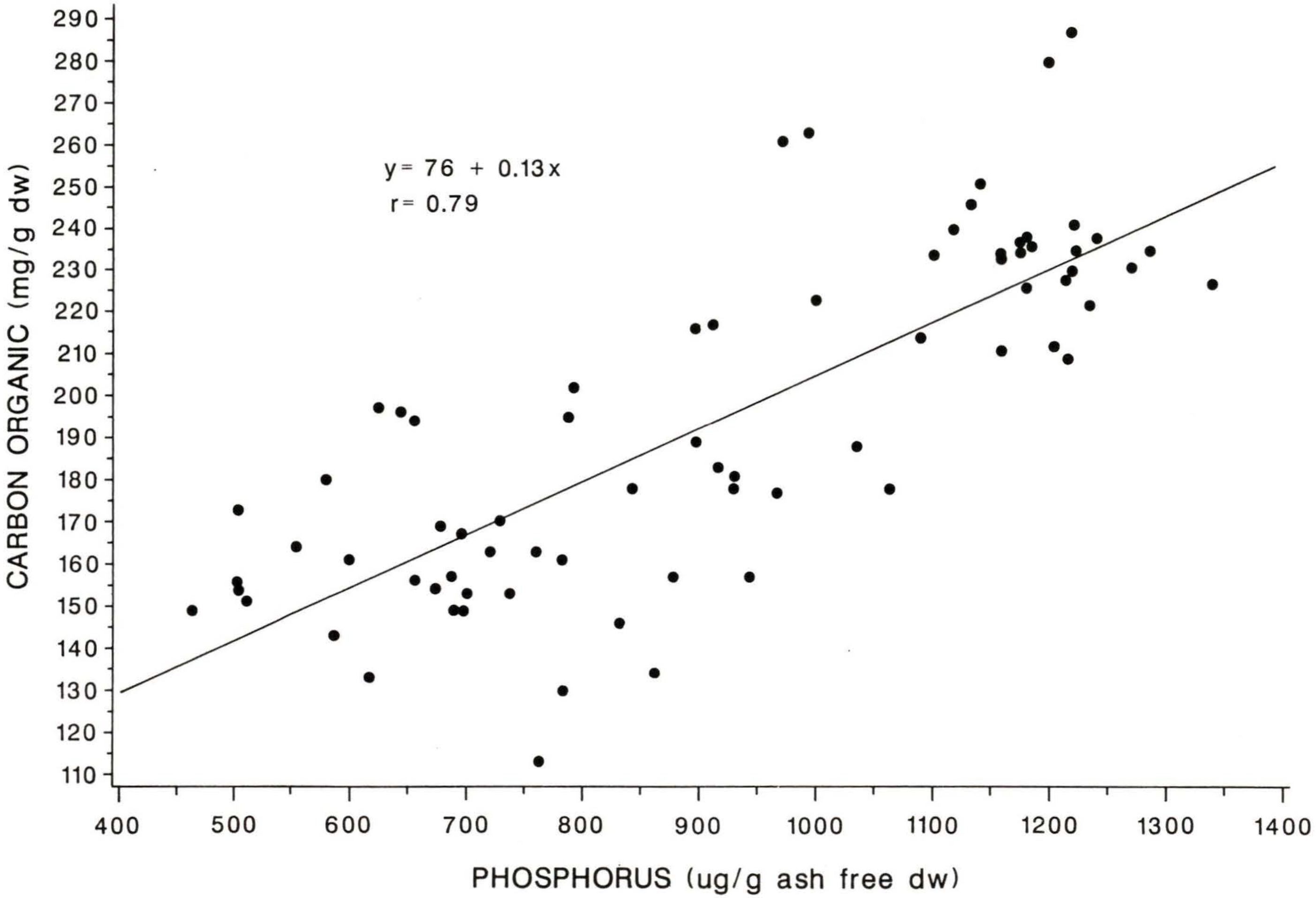
The organic carbon concentration in the surface sediments of Langford Lake averaged 210 mg/g (dw) (Table 8) or 0.0175 moles/g. Based on molarity, carbon in the organic form is the most common element of the organic fraction. The surface concentrations of organic carbon is negatively correlated with water depth, which accounted for 67% of the observed within-lake variability. The decrease in the organic fraction with increasing water depth in Langford Lake is thought to be caused by two separate processes. First, phytoplankton contain very litte structural organic carbon, and much of it is decomposed within the water column (Godshalk and Wetzel, 1976). Increased water depth affords more time for the decomposition of detritus in the water column (Anderson and Jacobsen, 1979). Pennington (1974) observed that sediment traps in deeper waters of the English Lakes District frequently collected smaller quantities of dry matter due to differences in water column decomposition. Second, turbulence, primarily caused by intermittent complete mixing (Hilton, 1985) at fall overturn, or by wind (Bloesch and Uehlinger, 1986), resuspends sediments and is the principal cause of sediment focusing (Likens and Davis, 1975; Davis and Ford, 1982; Bloesch and Uehlinger, 1986; and Hilton et al., 1986). The depth of turbulent displacement of surface sediments at fall overturn averaged 2-22 mm in Esthwaite Water (Gorham, 1958). During the resuspension, the sediments become reoxidized which affords additional organic decomposition. Because of sediment focusing, the sediments in the deeper points in the lake are generally older, and have been decomposed under aerobic conditions longer than the sediments in the shallower areas.

The horizontal distribution of organic carbon from other lakes increases with increasing water depth (e.g., Bantam Lake, Connecticut: Frink, 1969; Lake Mendota, Wisconsin: Brock, 1985; Lake Arungen, Norway: Skogheim, 1977; and the Great Lakes: Thomas et al., 1972, Thomas et al., 1973, Thomas et al., 1976). In all of the above studies, the lakes had high clastic inputs, consequently a decrease in the clastic content with increasing water depth (due to decreased wave turbulence) is the principal reason for the increased organic carbon concentrations.

Langford Lake appears to be unique in that the clastic content of the hypolimnetic sediments is insignificant, and the influence of sediment focusing and water depth on the decomposition and sedimentation of organic content is demonstrated.

The vertical distribution of organic carbon showed two important trends (Figure 25). First, the organic content increased in Zone P2 due to decrease clastic loading (the result of stabilization of soils and landforms in the watershed). Second, the highest organic carbon concentrations are observed at 10.65 m (the interface between Zones P2 and P3), and the surface sediments. Both organic carbon peaks corresponded with increased sediment phosphorus concentrations. The correlation of organic carbon and phosphorus in the Holocene sediments of Langford Lake (Figure 36), combined with the observation that the primary production of Langford Lake is limited by the availability of phosphorus (Schindler, 1974; Nordin and McKean, 1984; Dillon and Rigler, 1974; McKean and Munteanu, 1981), indicates that the autochthonous organic component of lake sediments is determined by the phosphorus concentration of the water. Consequently, increased phosphorus loading would result in elevated organic carbon and phosphorus concentrations in the sediments.

Figure 36: Sediment Organic Carbon Concentrations (mg/g dw) as a Function of Sediment Phosphorus Concentrations (μg/g ash free dw) in Langford Lake


y= 76 + 0.13x
r= 0.79
CARBON ORGANIC (mg/g dw)
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
400
500
600
700
800
900
1000
1100
1200
1300
1400
PHOSPHORUS (ug/g ash free dw)

The organic carbon content of the sediments, in association with the primary production of a lake (measured by spring overturn phosphorus concentrations), is the principal factor determining the redox potential at the sediment-water interface of the hypolimnetic sediments (McKean, 1986). The redox potential in turn is very important because it determines the solubility of iron and manganese minerals (Sections 5.6 and 5.8), and the rate of internal phosphorus loading (Section 5.10b).

The link between autochthonous organic production and the organic content of the sediments is a fundamental assumption in fresh water ecology. However, it is difficult to demonstrate in limnetic situations because the input of allochthonous organic and inorganic materials mask the relationship.

5.6 IRON

Iron is a major consituent of the bedrock geology of Langford Lake, comprising 60 mg/g (Table 16). In contrast, the surface sediment iron concentrations are 50% lower at 28.5 mg/g ash free dw, which indicates a large portion of the iron is transported through the lake without precipitating to the sediments.

In bedrock, iron occurs largely as ferromagnesium, but precipitates as ferric (Fe(III)) oxides and hydroxides during weathering. The solubility of iron in water is largely governed by Fe(III) precipitates (ferric hydroxide, geotite, etc.), while hydrolysis, complexation, and redox are important modifying factors (Lindsay, 1979). In water, small quantities of iron become dissolved according to the following reaction:

$$\mathrm{Fe(OH)_3}\ \text{amorp.} + 3\mathrm{H^+} \rightleftarrows \mathrm{Fe^{3+}} + 3\mathrm{H_2O} \qquad \log K^\circ = 3.54$$

The $\mathrm{Fe^3}$ ion is surrounded by six molecules of water. Increased pH removes H^+ from the coordinated waters giving rise to the various Fe(III) hydroxides:

$$\begin{array}{llcll}
FeOH^{2+} & + H^+ & \rightleftharpoons & Fe^{3+} & + H_2O \\
Fe(OH)_2^+ & + 2H^+ & \rightleftharpoons & Fe^{3+} & + 2H_2O \\
Fe(OH)_3^0 & + 3H^+ & \rightleftharpoons & Fe^{3+} & + 3H_2O \\
Fe(OH)_4^- & + 4H^+ & \rightleftharpoons & Fe^{3+} & + 4H_2O
\end{array}$$

The solubilities of the Fe(III) hydroxides are influenced by pH (Figure 37). Below pH 7.3, $Fe(OH)_2^+$ is the dominant ion species, while the solubility of Fe^{3+} decreases 1000 fold for every unit increase in pH. The activity of Fe^{3+} is of considerable interest in eutrophication studies because it is the Fe^{3+} ion that binds with orthophosphate to form strengite ($FePO_4 \bullet 2H_2O$; Lindsay, 1979). The formation of strengite (equation below) is stable under oxidized conditions and limited by the activity of Fe^{3+}.

$$Fe^{3+} + H_2PO_4^- + 2H_2O \rightleftharpoons FePO_4 \bullet 2H_2O + 2H^+$$

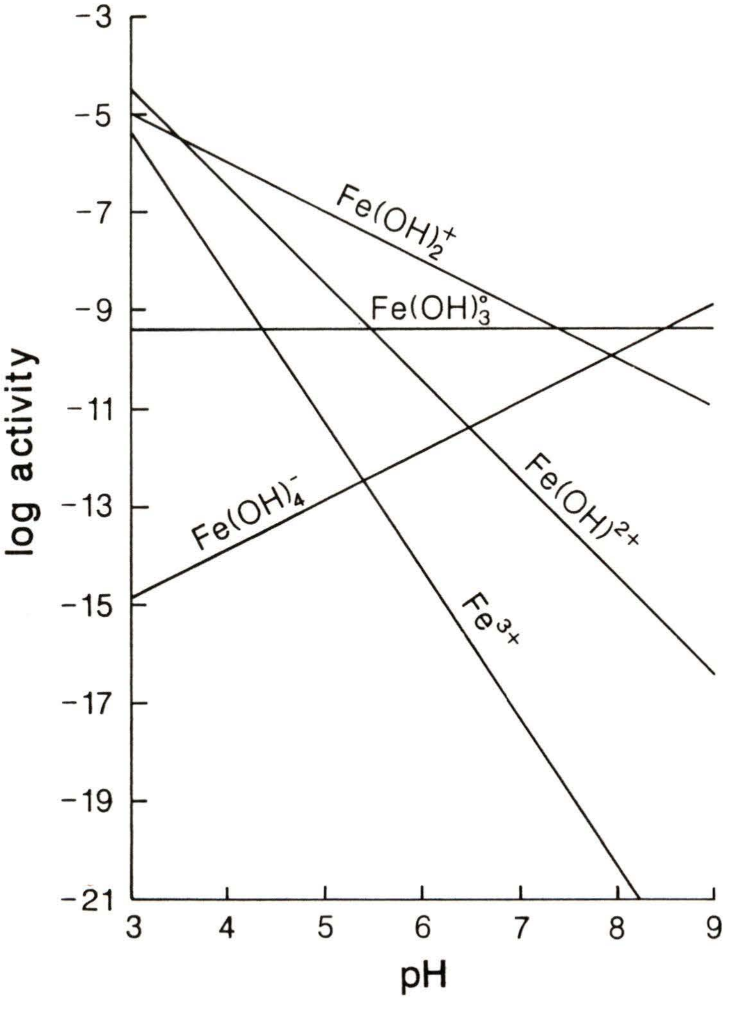
(strengite)

($\log K^\circ = -6.85$ from Lindsay, 1979)

Stauffer (1985) noted that the decrease in Fe^{3+} activity with increasing pH would reduce strengite formation and increase $H_2PO_4^-$ activity in the hyplimnion. The hydroxyl inactivation of Fe^{3+} is the principal reason that hard water lakes with $pH > 8.0$ are more productive than soft-water lakes (Stauffer, 1985).

The addition of Fe(III) as $FeCl_3$ (Nordin, 1987), or the acidification of a lake (Nordin et al., 1983) have been proposed as lake

Figure 37: The Effect of pH on the Hydrolysis Species of Iron (from Lindsay, 1979)


log activity
-3
-5
-7
-9
-11
-13
-15
-17
-19
-21
3
4
5
6
7
8
9
pH
$Fe(OH)_2^+$
$Fe(OH)_3^\circ$
$Fe(OH)_4^-$
$Fe(OH)^{2+}$
Fe^{3+}

restoration techniques in eutrophic lakes that release orthophosphate from sediments under reducing conditions. These techniques are designed to increase the Fe^{3+} activity and phosphorus binding capacity of the sediments.

Reducing conditions will also decrease the activity of Fe^{3+} ions by conversion to Fe^{2+}. For every decrease in one pe (negative log of electron activity) unit, the Fe^{3+} activities will decrease 10-fold.

$$Fe^{3+} + e^{-} \rightleftharpoons Fe^{2+} \quad \log K^{0} = 13.04$$

from Lindsay (1979)

Reducing conditions within the sediments are caused by the decomposition of organic matter by heterotrophic bacteria (Wetzel, 1983). In oxidized sediments, the redox potential (E_H) is controlled by oxygen. Following oxygen depletion, other compounds serve as electron acceptors, and electron activity increases as available electron acceptors are utilized.

In sediments and natural waters, the major electron acceptors include O_2(pe = 13.72), NO_3^-(pe = 12.65), MnO_2 (pe=8.5), Fe^{3+}(pe = -1.67), and SO_4^{2-} (pe = ¯3.75) (Stumm and Morgan, 1970). Reduction of Fe^{3+} begins soon after oxygen depletion, but the onset of reducing conditions will be slowed proportionately by the amounts of NO_3^- and MnO_2 present (Lindsay, 1979).

The activity of Fe^{2+} increases under reducing conditions, unless the Fe^{2+} activity exceeds the saturation point of a Fe(II) mineral (e.g. magnetite). At pe + pH <11.53, the activity of Fe^{2+} will exceed the solubility of magnetite (Fe_3O_4), causing magnetite to precipitate. With time, under reducing conditions, all Fe(III) minerals will be converted to Fe(II) minerals. When the sediments are reduced, the solubility of Fe(III) and Fe(II) minerals changes, and this in turn affects the solubilities of iron - phosphate minerals (Williams et al., 1971).

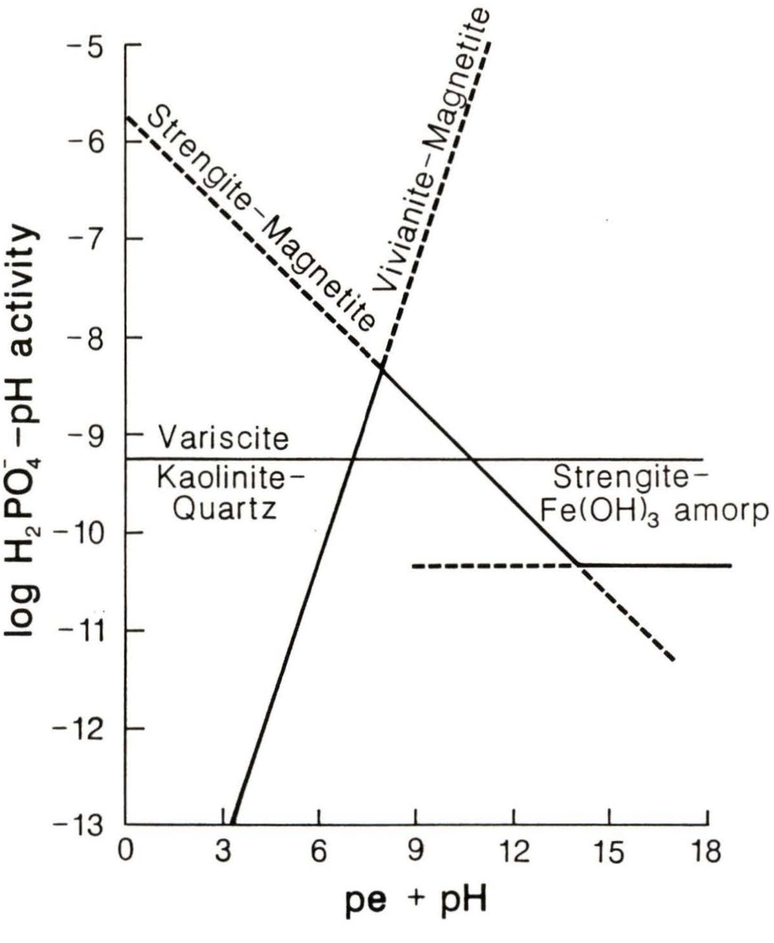
The effect of pe + pH on the solubility of the principal iron-phosphate minerals and the activity of orthophosphate is plotted in Figure 38 using the equilibrium equations developed by Lindsay (1979). Above a pe + pH>11.5 conditions are considered oxidizing and $Fe(OH)_3$ (amorp.) would be the stable Fe(III) mineral, Fe^{3+} would be the principal iron species in water, strengite would be the stable iron-phosphate mineral, and the activity of orthophosphate would remain constant ($\log K^0\ H_2PO_4^- - pH = {}^-9.55$). Below a pe + pH of 11.5, magnetite would be the stable Fe(II) mineral, and Fe^{3+} would be the principal iron species in water.

The activity of orthophosphate under these conditions is still controlled by strengite; however, strengite's solubility and orthophosphate activity increases with decreasing redox potential. The influence of redox potential on the solubility of strengite is one important mechanism that causes the release of orthophosphorus from the sediments.

The solubility of strengite decreases with decreasing redox until a pe + pH of 7.9. Below this point vivianite will be the stable iron-phosphate mineral. Under extreme reducing conditions (pe+pH<6.0) vivianite has the potential to lower the activity of orthophosphate below the activity observed under oxidizing conditions. However, in practice the formation of vivianite is not observed in lake sediments or soils because of the reaction of reduced sulphur compounds with Fe^{2+} (Lindsay, 1979). The formation of iron monosulphides is very stable under reducing conditions.

$$Fe^{2+} + S^{2-} \rightleftarrows FeS \qquad \log K^\circ = 16.21$$

Figure 38: The Effects of Redox on the Solubilities of Strengite, Variscite, and Vivianite (from Lindsay, 1979)


Strengite-Magnetite
Vivianite-Magnetite
Variscite
Kaolinite-
Quartz
Strengite-
Fe(OH)$_3$ amorp
log $H_2PO_4^-$-pH activity
-5
-6
-7
-8
-9
-10
-11
-12
-13
0
3
6
9
12
15
18
pe + pH

The presence of reduced sulphur (S^{2-}) will release orthophosphate from vivianite by the following reaction:

$$\underset{\text{vivianite}}{Fe_3(PO_4)_2 \bullet 8H_2O} + 3S^{2-} \rightleftharpoons 3FeS + 2H_2PO_4^- + 6H_2O + (OH^-)_2$$

$$\log K^\circ = 19.32$$

from Lindsay (1979)

The inactivation Fe(II) minerals by reduced sulphur is another mechanism by which orthophosphate is released from sediments. The bubbling of hydrogen sulphide through sediments (in the laboratory), and the subsequent determination of orthophosphorus concentration in solution, will determine the degree of phosphorus release expected from iron minerals (Ripl, pers. comm.). The presence of hydrogen sulphide in the hypolimnion of lakes indicates that all the iron (and iron-phosphate minerals) in the sediments have been converted to iron monosulphides, and that internal phosphorus loading has occurred (Schindler, pers. comm.).

The iron cycle in lakes is principally controlled by the reducing conditions that develop below the sediment-water interface (Davison et al., 1982). Under reducing conditions Fe^{3+} ions are converted to Fe^{2+} ions, and the concentration of $Fe(OH)_3$ decreases accordingly because it is in equilibrium with the Fe^{3+} ion (Lindsay, 1979). The solubility of the Fe^{2+} ion is much higher than the Fe^{3+} ion, and it diffuses along a concentration gradient across the sediment-water interface into the hypolimnion, and then into the epilimnion by eddy diffusion. In the presence of oxygen, the reduced iron becomes oxidized and precipitates as amorphous iron hydroxide to the sediment-water interface (Davison et al., 1982). The accumulation of amorphous iron hydroxide at the sediment-water interface is described by Mortimer (1941, 1942, & 1971) as the oxidized microlayer. Syers et al. (1973) describes the same layer as a Fe-rich gel complex.

Differential iron extraction from the Langford Lake sediments (McKean, unpubl.) indicates that the majority of the iron is associated with the oranic fraction, while the majority of the inorganic iron is noncrystalline amorphous.

Unlike the other elements, the surface iron concentrations are not strongly correlated with elements associated with the organic or inorganic components (Table 12). Iron is significantly correlated with organic carbon, but the correlation does not account for more than 45% of the observed within-lake variability (Table 12). Iron was also significantly correlated with manganese and phosphorus, suggesting that the solubility of inorganic iron minerals is influenced by the redox potential, and iron is influencing the horizontal distribution of phosphorus, presumably through the precipitation of iron-phosphate minerals.

The association of iron with both the organic and inorganic components of the sediments resulted in an unusual horizontal distribution (Figure 13). Iron is not correlated with water depth (r=-0.41), distance from shore (r=0.16), or weed beds (r=0.10, Table 13). In contrast, iron concentration are significantly correlated (r=0.74) with water depth in Lake Mendota (Brock, 1985), primarily because of decreases in clastics with increasing water depth. The distribution of the iron rich non-clastic sediments in Lake Mendota are determined by wind induced hypolimnetic currents (Brock, 1985).

The horizontal distribution of iron in Fontana Lake, (North Carolina) is elevated near the inflow rivers, which is the primary source of iron in the lake (Abernathy et al., 1984). The inflows to Langford Lake were much more diffuse and would not be expected to influence the iron distributions.

The vertical distribution of iron is typical of the inorganic elements influenced by weathering. Iron is strongly associated with the inorganic fraction (Factor 2, Table 14), and highly correlated (>0.90) with aluminum, magnesium, and manganese (Table 15). The maximum iron concentrations (60 mg/g ash free dry weight) were recorded immediately after deglaciation and decreased consistently in Zones P2 and P3 (Figure 26). Iron concentrations remained constant (15 mg/g ash free dw) in the latter portions of Zone P3 (8.8 m), and through zones P5 and P6 which indicates that the iron loading from the watershed had stabilized after the Mt. Mazama eruption (6,600 BP). The Mt. Mazama eruption briefly lowered the iron concentration due to the presence of tephra in the core. Following the eruption, iron concentrations are briefly elevated due to increased metal loadings from the tephra.

The constant iron concentrations in Zones P5 and P6 indicated little or no effect of watershed development or climatic changes on iron loading to Langford Lake.

5.7 MAGNESIUM

The magnesium content of the bedrock geology in the Langford Lake watershed is 27 mg/g (Table 16), however, the average magnesium content of the sediments is much lower (3.7 mg/g ash free dw). The lake sediments within the Coastal Douglas Fir Biogeoclimatic Zone also have low magnesium concentrations (4.4 mg/g; McKean unpubl.), because of the high solubility of magnesium in water (Lindsay, 1979).

In noncalcareous geologies, magnesium is primarily associated with primary silicate minerals or secondary minerals such as aluminosilicates. The weathering of a typical magnesium-silicate mineral is given below.

$$\underset{\text{sepiolite}}{Mg_2Si_3O_6(OH)_4} + 2H_2O + 4H^+ \qquad 2Mg^{2+} + 3H_4SiO_4^0$$

$$\log K^0 = 15.9 \qquad \text{(from Lindsay, 1979)}$$

Although the dissociation constant for magnesium minerals is usually higher than for calcium minerals (Section 5.4), indicating higher rates of weathering, the magnesium water concentrations in Langford Lake are lower because magnesium is less common in the bedrock geology.

The solubility of magnesium minerals in water under saturated conditions is illustrated in Figure 39. Amorphous magnesium-silicate (Soil-Mg) predominates below pH 7.8, while dolomite ($CaMg(CO_3)_2$) is the stable mineral above pH 7.8. The activities of the three most common magnesium complexes in equilibrium with soil-Mg or dolomite are shown in Figure 40. Mg^{2+} is the predominant ion below pH 9.2. Below pH 7.7 the activity of Mg^{2+} is constant at 10^{-3} moles/L (100 mg/g). The concentration of magnesium in Langford Lake (3-4 mg/L) is well below saturation point of soil-Mg or dolomite; consequently, the formation of the inorganic minerals will not occur or be observed in the Langford Lake sediments.

The magnesium observed in the Langford Lake sediments is associated with the clastic materials deposited in the lake by erosion. The surface concentration of magnesium is strongly associated with the inorganic fraction of the sediments (Factor 2, Table 11). The elements within this group are moderately correlated with water depth ($r=^{-}0.63$), but their spatial distributions appear to be influenced by the erosion of clastic materials from the littoral zones (Figure 15).

The maximum magnesium concentrations (17.2 mg/g ash free dw) in Langford Lake are recorded in Zone P1 (the period of maximum erosion). All other inorganic elements (Fe, Mn, P), except aluminum, had depressed concentrations in this zone because of the high degree of clastic loading. In the case of magnesium, the weathering of the clastic materials deposited in the lake would result in dissolution of magnesium in the secondary minerals to Mn^{2+}. Consequently, because of its high solubility, the concentration of magnesium is related to the

Figure 39: The Effects of pH on the Solubility of Soil-Mg, and Dolomite (from Lindsay, 1979)

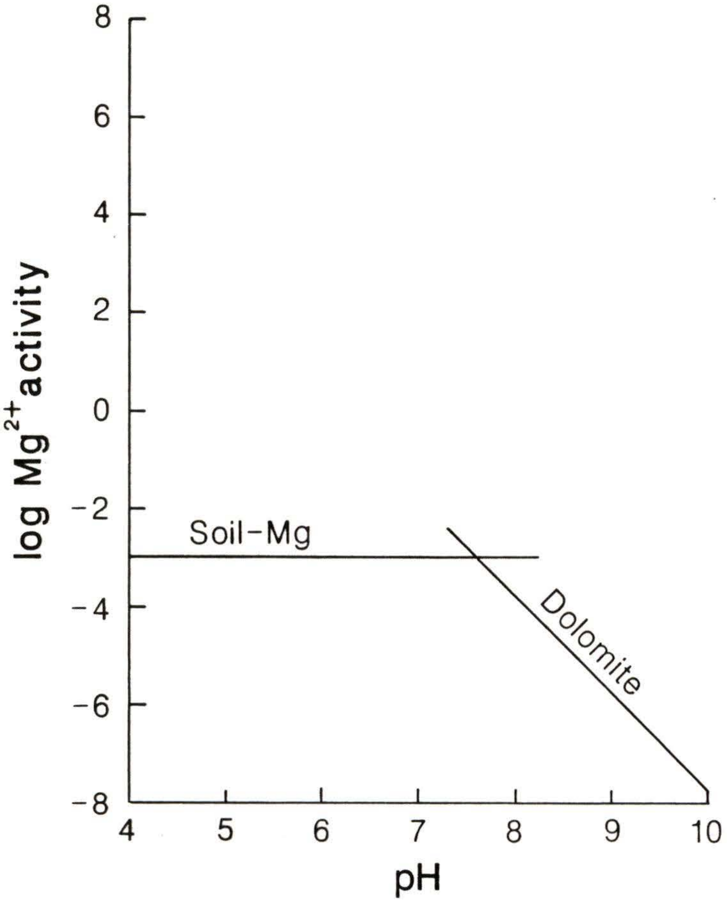
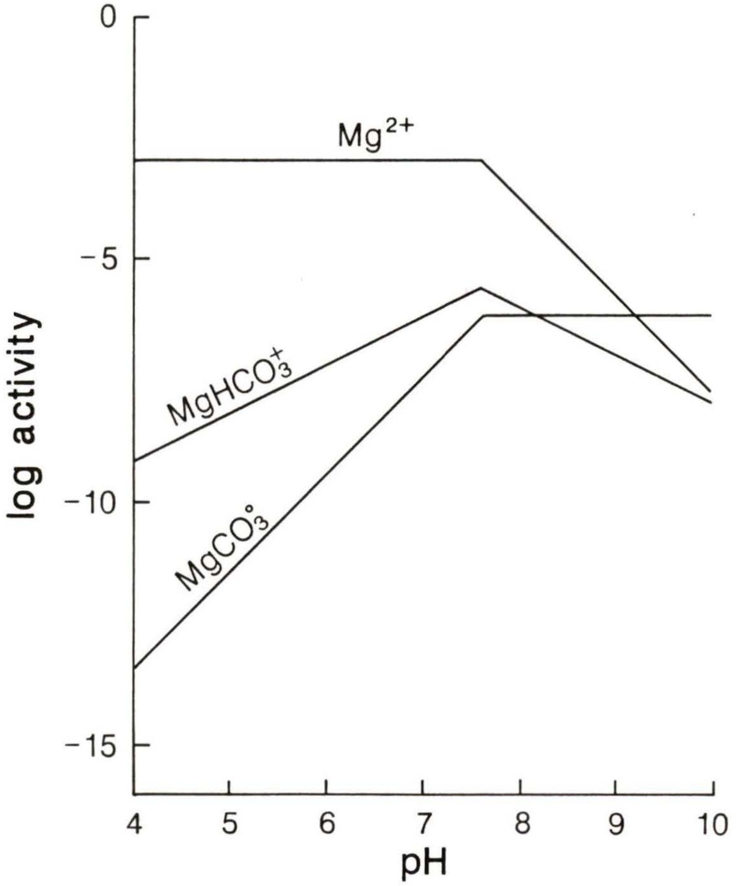

8
6
4
2
0
-2
-4
-6
-8
log Mg^{2+} activity
Soil-Mg
Dolomite
4
5
6
7
8
9
10
pH

Figure 40: The Effects of pH on the Activities of Magnesium Ions in Equilibrium with Dolomite (from Lindsay, 1979)


0
-5
-10
-15
log activity
4
5
6
7
8
9
10
pH
Mg^{2+}
$MgHCO_3^+$
$MgCO_3^\circ$

clastic component of the lake sediments, which is a reflection of the rates of erosion in the watershed (Mackereth, 1966).

Magnesium concentrations decreased in Zone P2 and P3 to a constant concentration of around 2 mg/g ash free dw (Figure 27). The Mount Mazama eruption (6600 years BP) temporarily increased the magnesium content of the sediments. Magnesium concentrations remained constant through Zone P5, but appear to increase marginally in P6, presumably because of the increased erosion associated with land clearing, road and railway construction.

The association of magnesium with the clastic component of the lake sediments supports Mackereth's hypothesis (Mackereth, 1966), that magnesium is transported to a lake with the products of erosion rather than the products of weathering.

5.8 MANGANESE

Manganese is less abundant than either aluminum or iron, with an average of 1.0 mg/g in the bedrock geology around Langford Lake, and 0.9 mg/g ash free dw in the lake's sediments. The most stable manganese mineral under well-oxidized conditions is pyrolusite (β-MnO_2). The equilibrium reaction of pyrolusite with Mn^{2+} at 25°C is:

$$\beta MnO_2(\text{pyrolusite}) + 4H^+ + 2e^- \rightleftharpoons Mn^{2+} + 2H_2O$$

$$\log K^\circ = 41.89$$

(from Lindsay, 1979)

The effect of redox and $CO_{2(g)}$ on the solubility and stability of manganese is shown in Figure 41. When the pe+pH reaches 16.62 the solubility lines of β-MnO_2 (pyrolusite) and γ-MnOOH (manganite) cross, and the minerals coexist. With further reduction the solubility of manganite coincides with $MnCO_3$ (rhodochrosite). The point of intersection depends on the activity of the $CO_{2(g)}$.

The solubility of Mn^{2+} in sediments appears to be governed by pyrolusite above pe + pH of 16.62, by manganite at slightly lower redox, and by rhodochrosite at still lower redox depending upon the partial pressure $CO_{2(g)}$. The solubility of manganese minerals is also strongly influenced by pH, exhibiting a 2-fold increase for each unit decrease in pH (Figure 42).

Manganese forms many soluble species, of which Mn^{2+} is predominant, and the activity of Mn^{2+} is strongly related to redox (Figure 41) and pH (Figure 42). Manganese in the form of Mn^{2+} can bind with orthophosphate to form two stable compounds:

$$\begin{array}{lr} & \log K^\circ \\ Mn^{2+} + H_2PO_4^- \rightleftharpoons MnHPO_4 + H^+ & 5.74 \\ 3Mn^{2+} + 2H_2PO_4^- \rightleftharpoons Mn_3(PO_4)_2^+ & -11.78 \end{array}$$

from Lindsay (1979)

The solubilities of the manganese-phosphate minerals are summarized in Figure 43. Based on the solubility of $MnHPO_4$, this mineral is very stable, and is more stable than strengite below a pe + pH <19. Unfortunately there is little information on the importance of manganese-phosphate minerals in lake sediments relative to strengite and vivianite (Lindsay, 1979). The relative importance of phosphorus binding with manganese is discussed in Section 5.10.

The mean concentration of manganese in the surface sediments of Langford Lake (0.77 mg/g ash free dw) is similar to the concentration in the bedrock. The within-lake variability of manganese (39%) was the highest of the elements analyzed (Table 10). The reason for the high variability is not know.

In the surface sediments, manganese is moderately correlated with

Figure 41: The Effects of Redox Potential, pH, and CO_2 on the Solubility of Manganese Minerals (from Lindsay, 1979)

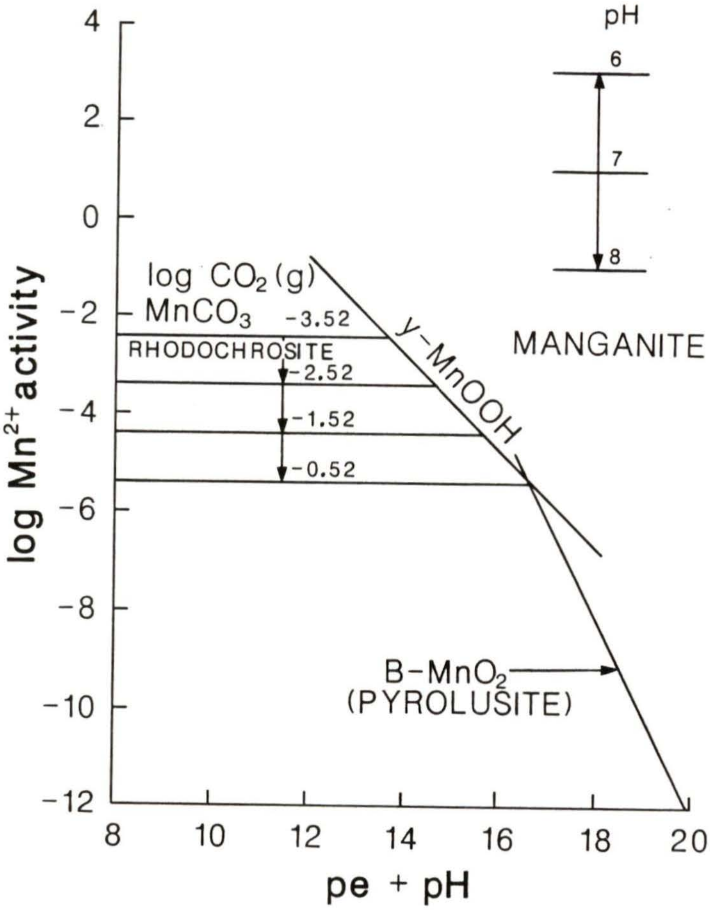

log Mn^{2+} activity
pe + pH
4
2
0
-2
-4
-6
-8
-10
-12
8
10
12
14
16
18
20
pH
6
7
8
log CO$_2$(g)
MnCO$_3$
-3.52
RHODOCHROSITE
-2.52
-1.52
-0.52
y-MnOOH
MANGANITE
B-MnO$_2$
(PYROLUSITE)

Figure 42: The Effects of pH on the Solution Species of Manganese in Equilibrium with Manganite and Pyrolusite (from Lindsay, 1979)

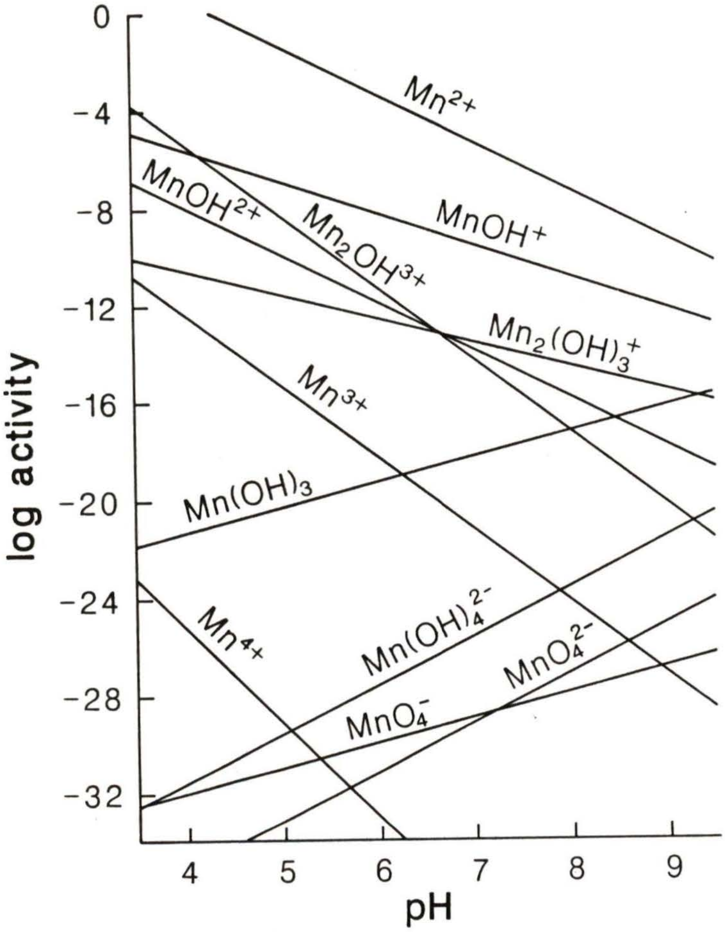
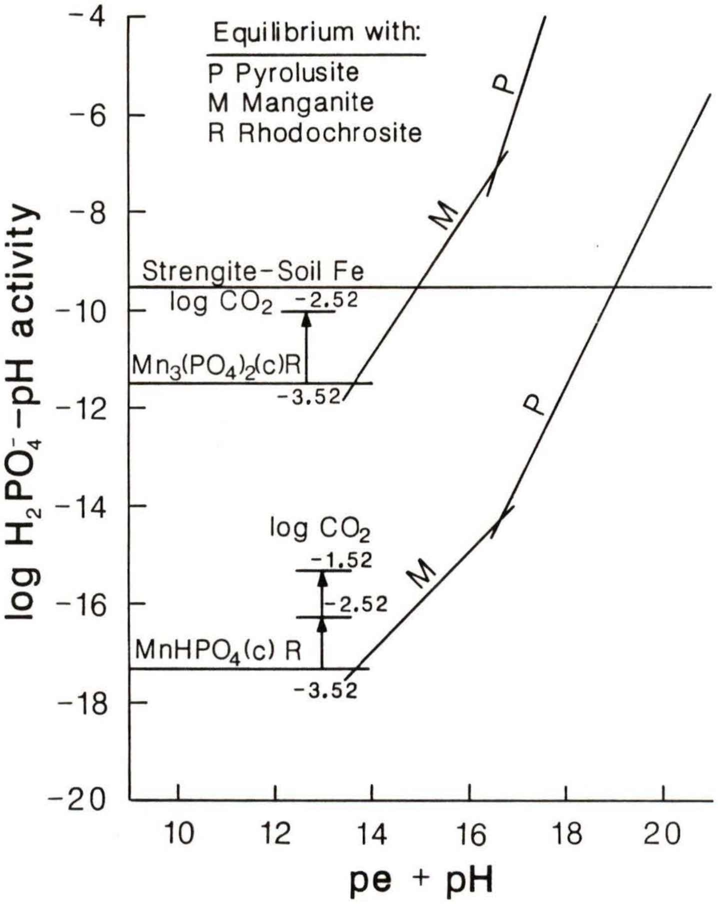

0
-4
-8
-12
-16
-20
-24
-28
-32
log activity
4
5
6
7
8
9
pH
Mn^{2+}
$MnOH^{+}$
$MnOH^{2+}$
Mn_2OH^{3+}
$Mn_2(OH)_3^+$
Mn^{3+}
$Mn(OH)_3$
Mn^{4+}
$Mn(OH)_4^{2-}$
MnO_4^{2-}
MnO_4^-

Figure 43: The Solubility of Manganese Phosphates Relative to Strengite


Equilibrium with:
P Pyrolusite
M Manganite
R Rhodochrosite
Strengite-Soil Fe
log CO2
-2.52
-3.52
Mn3(PO4)2(c)R
log CO2
-1.52
-2.52
-3.52
MnHPO4(c) R
P
M
P
M
log H2PO4- -pH activity
-4
-6
-8
-10
-12
-14
-16
-18
-20
10
12
14
16
18
20
pe + pH

water depth. However, manganese had a lower correlation coefficient (when compared with calcium), presumably because of the influence of reducing conditions (see Section 5.4) on the solubility of manganese minerals.

The vertical distribution of manganese is typical of the other elements that are associated with the leaching of weathered minerals. High concentrations of manganese are recorded immediately after deglaciation, representing a period of rapid weathering of manganese from the disturbed soils and landforms. Manganese concentrations decreased from a peak at 10.65 m, to a constant concentration after the Mount Mazama eruption (Figure 36). Concentrations remained stable until 1.4 m when concentrations increased to approximately 450 µg/g ash free dw. The increase is thought to represent the effects of watershed development on sediment manganese concentrations.

5.9 NITROGEN

Nitrogen in lakes is very similar to organic carbon in that its origin is atmospheric, and not derived from the erosion or weathering of geological deposits. The cyanobacteria are the principal nitrogen fixers in the lotic environment, whereas heterotrophic nitrogen fixing bacteria (e.g. *Nitrosomonas* spp.) occur in the terrestrial and littoral environments (Wetzel, 1983). In eutrophic conditions nitrogen fixation in lakes can approach 2 mg N m^{-2} day^{-1} (Wetzel, 1983).

Decomposition of organic nitrogen produces nitrate under oxidized conditions and ammonia under anoxic conditions. Nitrogen can be lost from an aquatic system through the volatilization of ammonia, and N_2(gas) (microbial denitrification of nitrate, Wetzel, 1983).

The most common forms of nitrogen in water are ammonia, nitrate, and dissolved and particulate organic nitrogen. The majority of the sediment nitrogen occurs as particulate organic nitrogen (95%) and interstitial ammonia (Keeney et al., 1970; Ishirimah et al., 1976).

The horizontal and vertical distribution of Kjeldahl nitrogen (TKN) in the Langford Lake sediments mirror organic carbon. Because of the high correlations with organic carbon, TKN is considered a major component of the organic fraction. The factors affecting the horizontal and vertical distributions of Kjeldahl nitrogen are identical to organic carbon (See Section 5.5b).

The ratio of TKN to organic carbon depends on the environment in which the plants originated. Terrestrial and emergent plants require supportive materials (principally lignands) which are carbon rich and typically have a C:N ratio of 48:1. Microscopic algae do not require the supportive tissue; consequently, their C:N ratio is much lower (Hutchinson, 1957). The C:N ratio for Langford Lake in the surface and core sediments was approximately 10:1, indicating that the organic fraction in Langford Lake was autochthonous in origin throughout the Holocene period.

5.10 PHOSPHORUS

The phosphorus content of the bedrock geology around Langford Lake is approximately 1 mg/g (Table 19). Unlike the other inorganic elements the phosphorus content of the lake sediments (1.5 - 3.0 mg/g ash free dw) was higher than the surrounding bedrock geology, indicating phosphorus was being concentrated in the lake's sediments.

Sediment phosphorus is thought to be divided into four categories: orthophosphate sorbed on the surfaces of phosphorus-retaining compounds (nonoccluded); orthophosphate within the matrices of phosphorus-retaining components (occluded); discrete phosphorus minerals such as strengite, vivianite etc.; and organic esters of phosphoric acid (Williams et al., 1971). A high proportion of sediment inorganic phosphorus exchanged with labelled ^{32}P within a few hours, indicating much of the inorganic phosphorus is sorbed onto the surface of phosphorus-retaining components (Li et al., 1972). Lindsay (1979) noted that the chemical reactions within soils and sediments are sufficiently fast that amorphous complexes are formed, but will form more crystalline minerals (e.g. vivianite, and strengite) over time.

The phosphorus concentration of sediments is controlled principally by the more abundant cations of iron, aluminum, manganese, and calcium (Lindsay, 1979). In soft-water lakes, calcium is well below its saturation point; consequently, the formation of stable calcium-phosphate complexes will not occur (Avnimelech, 1975). The association of calcium with the organic fraction in Langford Lake (Section 5.4) confirms the absence of inorganic calcium-phosphate complexes.

The influence of manganese on the activity of orthophosphate is discussed in Section 5.8. Although the manganese-phosphate minerals are very stable under reducing conditions, manganese cannot be a principal factor controlling the orthophosphate activity in sediments of Langford Lake because the sediment molar ratio of phosphorus to manganese is 3:1 (Table 8). Williams et al. (1971) notes a weak statistical relationship between manganese and inorganic phosphorus in Wisconsin Lakes, which is accounted for by a manganese-iron interrelationship.

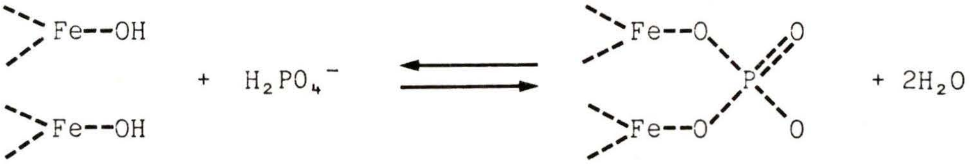
Williams et al. (1971) notes that the levels of inorganic phosphorus are closely related to the amount of hydrated iron hydroxide ($Fe(OH)_3$ amorphous) extractable by oxalate or CDB digestion. The sorption of orthophosphate by $Fe(OH)_3$ amorp. in the Wisconsin lakes (Williams et al., 1971), agrees with the classic work of Mortimer (1941 and 1942) in the English Lakes District, and Mortimer (1971) in the Great Lakes of North America. Nurnburg and Peters (1984) observed that 30% of the orthophosphate circulated in Lake Magog (Ontario) after fall overturn precipitates as an iron-orthophosphate complex, 30% is incorporated in the plankton, and the balance remaines in solution.

The formation of amorphous iron-orthophosphate, and to a lesser extent aluminum-orthophosphate complexes, will be the principal inorganic binding mechanism for orthophosphate in soft-water lakes. The formation of more crystalline minerals (e.g. strengite) is expected over time. The amorphous complexes will have different solubilities but will exhibit similar properties as the minerals (Lindsay, 1979).

a) Effects of pH on Phosphate Minerals

Both aluminum and iron-orthophosphate complexes are strongly influenced by increasing pH (Figure 32). Orthophosphate reacts with amorphous iron and aluminum by an "exchange adsorption" of hydroxyl ions for orthophosphate ions (Williams et al., 1971). Lijklema (1976) predicted binuclear adsorption (Reaction A) to explain the substitution of orthophophate and hydroxyl ions. Andersen (1975) proposed a similar hydroxyl-orthophosphate exchange (Reaction B).

A)



B)

$$\text{Fe--OH}^- + \text{HPO}_4^{-2} \rightleftharpoons \text{Fe--HPO}_4^- + \text{OH}^-$$

During periods of elevated pH, the high activities of OH^- will force the above reactions to the left, releasing orthophosphate into solution. Stauffer (1985) showed that the hydroxyl inactivation of iron and aluminum-orthophosphate complexes was the principal reason hard-water lakes (with high pH) had higher phosphorus and chlorophyll a concentrations than predicted by the Dillon and Rigler (1974) and Reckhow and Simpson (1980) phosphorus-chlorophyll models. The pH-mediated phosphorus release is most likely to occur in shallow productive lakes, where the pH is raised by one or two units due to intensive primary productively (Bostrom et al., 1982). The release of phosphorus under conditions of high pH will facilitate increased primary productivity in phosphorus limited situations.

b) Effects of Redox Potential

The effect of redox potential on the solubility of iron and iron-orthophosphate complexes is summarized in Figure 38. The solubility of aluminum-phosphate complexes is not affected by reducing conditions. This is an important consideration when lake restoration techniques are designed to increase the phosphorus binding capacity of sediments. The use of aluminum sulphate (alum) will increase the phosphorus binding capacity of the sediments, and the solubility of the aluminum-orthophosphate complex will not be influenced by redox potential.

Iron minerals, on the other hand, are strongly influenced by reducing conditions (Figure 38). Under oxidized conditions $FePO_4 \bullet 2H_2O$ will be the principal complex in the sediments by virtue of its greater solubility product. When the sediments become reduced, the solubility of amorphous $Fe(OH)_3$ and $Fe(OH)_2$ increases and this in turn increases the $FePO_4 \bullet 2H_2O$ solubility . The result is an increase in orthophosphate activity in the surrounding water.

Amorphous $Fe(OH)_2$ is converted to iron monosulphides when sulphate is reduced to S^{2-} by bacteria under reducing conditions (Section 5.6). Changes in the solubility of iron-phosphate minerals and the interaction of reduced sulphur compounds with iron are the principal mechanisms by which reducing conditions increase the activity of orthophosphate in solution.

c) Phosphorus Retention in Lake Sediments

Mortimer (1941, 1942) developed the classic model describing the retention of phosphorus within the sediments of soft-water lakes. In Mortimer's model, reducing conditions occur below the sediment-water interface, promoting the dissolution of $FePO_4 \bullet 2H_2O$ and resulting in high interstitial concentrations of reduced iron and orthophosphate. In lake sediments of the English Lakes District, where Mortimer conducted his research, the sediment-water interface has an iron rich oxidized microlayer. The oxidized microlayer forms an impermeable barrier to orthophosphate diffusion from the interstitial waters into the hypolimnion. The lakes within the Coastal Douglas Fir Biogeoclimatic Zone follow the classic model of Mortimer as long as the oxidized microlayer interface does not become reduced. Nurnburg et al. (1986) observed that the orthophosphate diffusion rates across the sediment-water interface were related to the trophic status of the lake. McKean (1986) related the trophic status of the lake to the redox potential at the sediment-water interface which in turn determined the concentration of orthophosphate in the hypolimnion.

Langford Lake, prior to aeration, followed Mortimer's model during the winter months when the sediment-water interface is oxidized (McKean and Munteanu, 1981). During summer stratification, decomposition of sediments and seston depleted the dissolved oxygen and created reduced conditions above the sediment-water interface. Orthophosphate and hydrogen sulphide were released from the sediments into that lake causing severe water quality problems at fall overturn (McKean, 1986).

d) Horizontal and Vertical Distributions

There are two possible explanations for the correlation between phosphorus and the organic fraction. First, phosphorus is bound to the organic fraction and released as the organics are decomposed. Second, phosphorus is bound to iron and aluminum minerals, and the decrease in pH and redox potential (associated with the decomposition of organic matter; McKean, 1986) accounted for its decrease with increasing water depth. Based on the discussion in Section 5.5, the latter hypothesis is more likely.

The vertical distribution of phosphorus was the most complicated of the elements discussed (Figure 30). Phosphorus concentration paralleled the inorganic elements associated with weathering (Fe and Mn) in Zones P1 - P3, which suggested that the phosphorus loading was elevated due to the leaching of residual phosphorus minerals from the glacial deposits. Phosphorus in the sediments indicated that phosphorus loading had stabilized in the xerothermic maximum in the same manner as iron and manganese. Phosphorus concentrations remained stable until Zones P5 and P6, when the phosphorus concentration increased at a relatively uniform rate. The reason for the increased concentrations in Zone P6 is attributed to watershed development. The elevation of phosphorus input to lakes as the result of watershed development has been clearly established (Rast and Lee, 1978; Rechow and Simpson, 1980; Dillon and Kirchner, 1975; and others). The explanation for the increased sediment phosphorus in Zone P5 is thought to be the result of increased phosphorus export coefficents caused by a shift from the grassland-Garry oak community of the xerothermic maximum to the present day coastal Douglas fir forest community (Section 4.3.3C.)

6. CONCLUSIONS

The physical appearance and chemical composition of the Langford Lake sediments can be explained by the interactions of climate (temperature, precipitation, etc.) on the geology and geomorphology of the drainage basin. The key components of the geology are historical events, and chemical composition of the bedrock geology, while the key components of geomorphology are the basin morphology (location, altitude, relief, etc.), and the maturation of the watershed (soil stability, anthropomorphic development, etc.).

The clastic content of the lake sediments is derived from the erosion of primary and secondary minerals from within the drainage basin. In Langford Lake the erosion was caused by the physical movement of the Vashon glaciers over the bedrock. The clastic content of lakes need not be associated with the erosion caused by glaciation. Lakes from the English Lakes District (Mackereth, 1966), Scotland (Pennington, 1981), and Vancouver Island (McKean, 1986) with high precipitation and relief had significant clastic content. In these situations the basin runoff has sufficient energy (vertical drop and volume) to erode within the soils and landforms into the lake.

The highly soluble elements of calcium, magnesium, chlorine, potassium, and sodium are frequently found in the clastic sediments. These elements are eroded and deposited in the lake before they can be solubilized from within the lattice matrix of the minerals by the weathering processes (Mackereth, 1966).

Calcium, and to a lesser extent magnesium, can be associated also with the organic fraction (incorporated in the chitin of crustaceans and insects), or with carbonates precipitated in the lake in arid areas (Muller et al., 1972; Wetzel, 1983). Calcium in Langford Lake is present in the clastic minerals deposited during the Vashon glaciation, but is primarily associated with the organic fraction. Magnesium, on the other hand, is exclusively associated with the clastic fraction.

The weathering of primary and secondary minerals, and the movement of the weathered compounds to the lake, determines the dissolved inorganic composition of the water. The precipitation of the weathered compounds (iron, manganese, and phosphorus) in the lake forms a small (< 5% of the inorganic fraction by weight) but important component of the lake sediments.

The weathering of minerals within the drainage basin primarily takes place in the soils. The contact time of the interstitial water with the minerals, and the solubility of the minerals will determine the concentrations of the dissolved constituents (Lindsay, 1979). The movement of the interstitial water (ground water) within the drainage basin is the principal vector of weathered inorganic compounds to a lake or waterbody. In areas of high precipitation, movement of ground water is greater and the contact time with the soil minerals is lower consequently, the concentrations of dissolved ions in the lake are lower.

The organic components of the Langford Lake sediments are primarily composed of carbon and nitrogen. The origin of the carbon and nitrogen is atmospheric gases, fixed by plants and bacteria, repectively, either within the drainage basin or the waterbody. The carbon:nitrogen ratio for Langford Lake is slightly below 10:1 indicating all the organic sediments are autochthonous in origin. Organic sediments dominated the surface and core sediments, and their concentrations are strongly correlated with the phosphorus content of the sediment.

The positive correlation indicates the rate of organic production and deposition (eutrophication) is linked to the weathering and leaching of phosphorus from the watershed. The effects of watershed development increase eutrophication in lakes through increased phosphorus loading. Lake restoration techniques designed to reduce eutrophication must focus on the reduction of phosphorus loading from the watershed, and the prevention of conditions within the hypolimnion of the lake which may cause phosphorus to be released from the sediments.

The sampling of lake sediments is very useful in understanding the interactions of the climate on the geology and geomorphology of the drainage basin, and the limnological processes within the lake. Future sediment studies should consider transects of surface sediment samples and at least one core from the deepest point in the lake. However, the chemical analyses of lake sediments should incorporate differential fractionation techniques (e.g. Williams *et al.*, 1971), to obtain a better understanding of the partitioning of the elements within the organic and inorganic fractions. The success of any sediment sampling program also depends on the regular analysis of water samples (for the determination of ionic balance, nutrient and metal cycling, etc.), and the ambient conditions within the lake (e.g. temperature, dissolved oxygen, pH, and pe).

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Appendix 1

DEVELOPMENT OF A CONTINUOUS PISTON CORER FOR ORGANIC SEDIMENTS

1. IMPACT CORERS

Wright *et al.*, (1965) attributed Lundquist in 1925 with describing the first impact corer: a weighted casing with wings (for stability) that was dropped from a boat and retrieved with a rope. Extra weights have been added (up to 2000 kg; McCoy, 1980) when deeper instrument penetration was required. Impact corers not using weight for momentum were quite rare. Piggot (1941) used cannon power, Isaacs and Brown (1968) developed the 'Bootstrap Corer' that used suction, while Ali (1984) used push rods in shallow lakes.

There are three major drawbacks inherent with the basic impact corer:

1) Stress reduction,
2) Core shortening,
3) Vertical instability.

In order to eliminate these problems in a variety of sediment types (clay → organic) and locations (deep sea, remote lakes, etc.), there have been a large number of modifications to the basic impact corer. Sections 1.1 → 1.3 outline the problems inherent with coring, and the different designs to overcome the difficulties.

1.1 STRESS REDUCTION

Stress reduction is caused by the partial or full vacuum formed below the casing when the corer is pulled from the sediment. The amount of sediment lost will depend on the length and diameter of the corer and the type of sediment. Coarse sandy sediments are not cohesive by nature, and are more influenced by stress reduction than are organic sediments (Burke, 1968). The most common method of limiting stress reduction is the addition of a check valve at the top of the casing. To be effective, the check valve must not hinder the movement of water through the casing during free-fall, yet must provide an adequate seal when the corer is retrieved. The most common designs using a check valve are the Phleger and Kajak corers (Phleger, 1951; and Kajak, 1969).

The Jenkin sampler (Jenkin et al., 1941) deployed a bottom seal in an attempt to eliminate stress reduction. Axelsson and Hakanson (1972) and Brinkhurst et al., (1969) also designed an impact corer with a bottom sphincter or seal for organic sediments, while Burke (1968) developed an effective nylon seal for use in coarse sandy sediments. A major drawback with the bottom seal design, however is their tendency to disturb the sediment-water interface (Williams and Pashley, 1979).

Shapiro (1956) developed a freeze impact corer in an attempt to reduce stress reduction in very soft organic sediments with "fluffy surface layers". Isaacs and Brown (1968) reduced stress reduction by allowing water to flow the length of the casing and fill the void left by the extracted corer.

1.2 CORE SHORTENING

Core shortening refers to the differences between instrument penetration and the amount of sediment collected in the casing (core penetration). A ratio of 1.0 indicates a perfect core with no core shortening. Emery and Dietz (1941) recorded a ratio of up to 0.5 in clayey or silty mud, while Hongve and Erlandsen (1979) observed a similar ratio in soft organic sediments. Core shortening is attributed to the buildup of water pressure within the casing and friction between the sediment and the inside walls of the casing or sample tube. The degree of core shortening varies with the design of the corer and the sediment type (clay, organic etc.).

a) Water Pressure

The restriction of water movement through the casing during a rapid descent creates a pressure wave ahead and within the casing. The pressure wave blows away the surface sediments at impact (Blomquist, 1985), while the pressure within the casing opposes the movement of sediment into the casing (Hvorslev, 1949). Water in the casing must be easily vented during descent to reduce the influence of water pressure on core shortening.

b) Wall Friction

The penetration of the corer into the sediments creates friction along the inner and outer walls of the casing. The outer wall friction reduces core penetration, while inner wall friction increases core shortening. Hvorslev (1949) determined inner wall friction as the most important factor causing core shortening.

Inner wall friction causes sediments within the casing to act like a plug, pushing the sediments below the casing into a cone (Figure 1). When the friction force exceed the shear strength of the sediment, no additional material will enter the casing (Hvorslev, 1949). Organic sediments have a higher water content and a lower shear strength, and are consequently more susceptable to core shortening than stiffer inorganic sediments (Hongve and Erlandsen, 1979).

Piggot (1941) and Blomquist (1985; Figure 2) showed a near-linear relationship between core shortening and instrument penetration, indicating that the friction forces were additive. Emery and Dietz (1941) demonstrated the cummulative influence of wall friction by dropping a casing 11 times into sediment without removing the accumu-

Figure 1: Deformation of sediment layers below an impact corer (modified from Hvorslev, 1949).

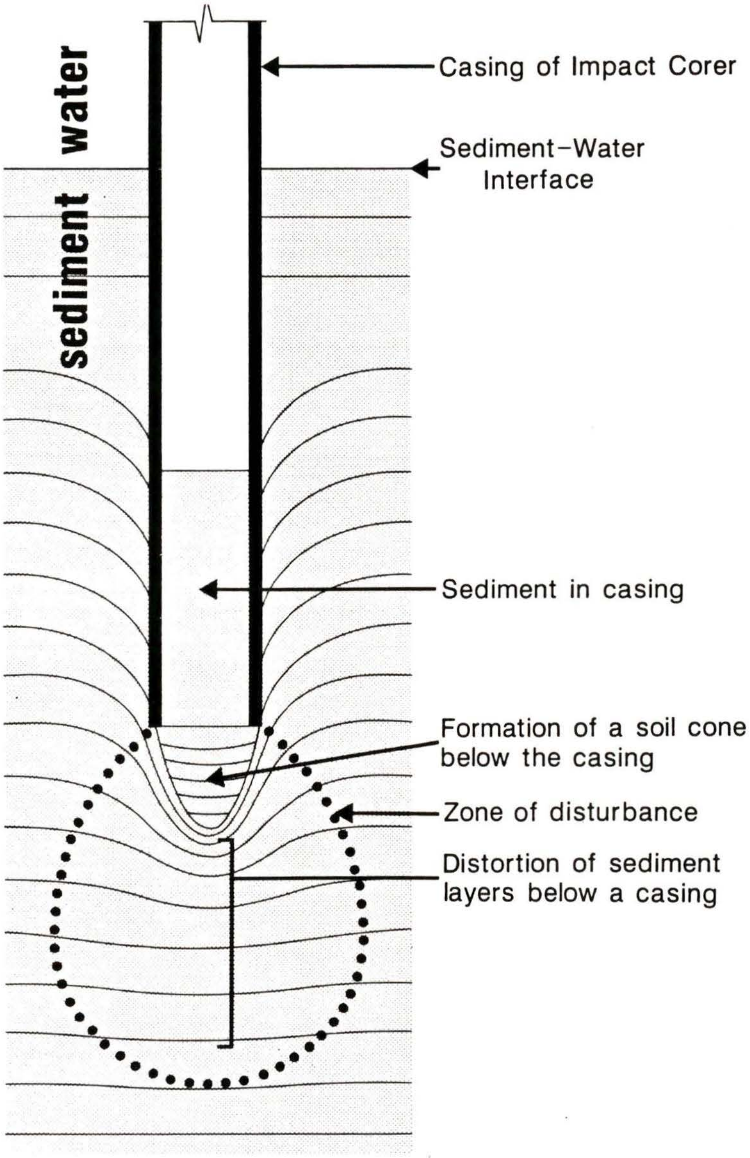
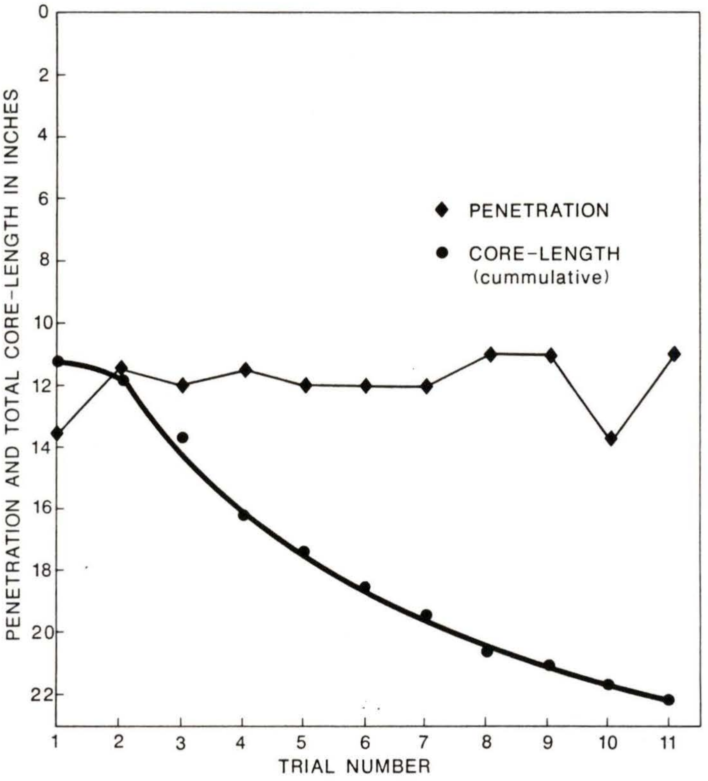

water
sediment
Casing of Impact Corer
Sediment-Water Interface
Sediment in casing
Formation of a soil cone below the casing
Zone of disturbance
Distortion of sediment layers below a casing

Figure 2: Amount of sediment core shortening as a function of penetration depth and core diameter. (Samples obtained by gently pushing plexiglass core tubes into the sediment; modified from Blomquist, 1985).


PENETRATION AND TOTAL CORE-LENGTH IN INCHES
0
2
4
6
8
10
12
14
16
18
20
22
◆ PENETRATION
● CORE-LENGTH (cummulative)
1
2
3
4
5
6
7
8
9
10
11
TRIAL NUMBER

lated sediment. With each successive drop, less sediment entered the casing (Figure 3).

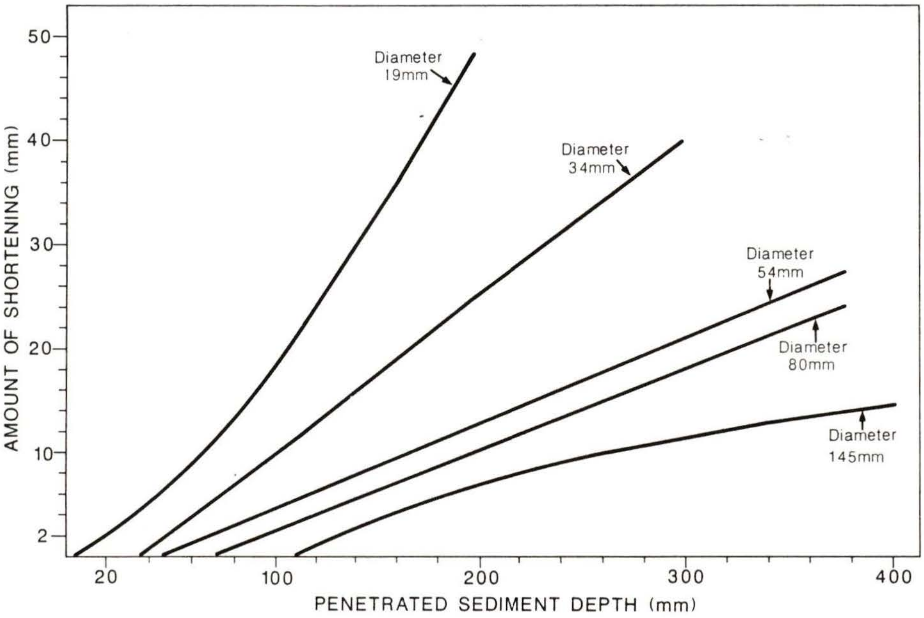
Piggot (1941) and Hvorslev (1949) recommended the addition of a cutting shoe with an inside diameter slightly less than the inside diameter of the casing. This design provides clearance between the sediment and the casing, reducing inner wall friction. Hvorslev (1949) recommended an inside clearance of 0.75 to 1.5 percent of the casings inside diameter. An inside clearance that is too large will cause the sediments to expand laterally in the casing. Too much lateral expansion will, in itself, cause significant core shortening (Emery and Dietz, 1941; and Hvorslev, 1949).

Wall friction is also reduced by increasing the diameter of the casing (Figure 2; Emery and Dietz, 1941; Piggot, 1941; and Blomquist, 1985). Core shortening decreased by 25 percent when the casing of a corer was increased from 2.06 inches to 2.4 inches (Emery and Dietz, 1941). Burke (1968) noted little disturbance (smearing, core shortening, etc.) of coarse sediments by a 21 cm diameter corer used for radionuclide studies. Casings with larger diameters have smaller friction forces per unit area because the crossectional area of the casing increases exponentially while its circumference increases linearly.

Wall friction can also be reduced by using casings with smooth inner surfaces, or competely eliminated with the use of sliding foils (Kjellman *et al*., 1950; and Livingston, 1967).

Wall friction causes surface sediments to be smeared along the length of the casing reducing the thickness of the surface layers (Wrath, 1936; and Ross and Reidel, 1967). Emery and Dietz (1941) observed the smeared layer to be not more than 1mm. Core shortening by this process is minor but becomes more important in longer cores.

Figure 3: The cummulative effects of wall friction on corer penetration and core length (modified from Emery and Dietz, 1941).


AMOUNT OF SHORTENING (mm)
50
40
30
20
10
2
20
100
200
300
400
PENETRATED SEDIMENT DEPTH (mm)
Diameter 19mm
Diameter 34mm
Diameter 54mm
Diameter 80mm
Diameter 145mm

1.3 VERTICAL PENETRATION

The third problem with impact corers is that while vertical penetration is assumed during free fall, it is rarely achieved. McCoy (1980) observed that over half the cores had inclinations between 5 to 8° from vertical. Twenty percent of the cores had inclinations between 9 and 12°, while only one third had inclinations less than 4°. The importance of vertical penetration is minor in short cores, but it becomes more important with long corers.

2. PISTON CORERS

Paleoecological studies require undisturbed, vertical cores free of core shortening. Corers utilizing a stationary piston are capable of virtually eliminating core shortening (Hvorslev, 1949). As described previously, core shortening is not completely eliminated since some surface sediments will be smeared against the inner wall of the casing, reducing the thickness of the surface layers (Wrath, 1936; and Ross and Reidel, 1967).

Kullenberg (1947) designed a long impact corer that used a trip mechanism to activate a stationary piston. The Kullenberg sampler was large, heavy, did not assure verticle penetration, and was not suitable for use in small boats. Livingston (1955) designed a light weight piston corer with a 1 m casing that used push rods to penetrate the sediments of relatively shallow lakes (<20m). The important feature of the Livingston corer is the ability to activate the piston up to 8 m below the sediment-water interface. This allows the complete stratigraphy of a small lake to be reconstructed from a series of one metre cores.

There are three major shortcomings of the Livingston design. Firstly, because of the flexibility of the push rods, the corer cannot be assured of vertically penetration or effectively used when the water depth exceeds 20 m (Mackereth, 1958; and Wright et al., 1965). Secondly, the corer segments are only 1 m in length, which disrupts the vertical sediment sequence and causes uncertainties in the stratigraphy. Thirdly, when pushing or jacking the apparatus through the sediments to sample the subsurface stratigraphy, a soil cone or bulb develops, causing downward disturbance of the stratigraphy similar to that caused by an impact corer (Figure 1; Hvorslev, 1949). Wright (1980) described the top of the Livingstone cores as slightly to greatly disturbed.

Long continuous piston corers were designed to provide less disturbance and more reliable stratigraphy. The casing of the Livingstone corer was extended to 7.5 m by Wright (1980), but the need for drive rods still limited its depth of use. Two alternate methods of forcing long continuous corers into sediments have been developed. Mackereth (1958) described a pneumatic corer with a 6 m casing. Barton and Burden (1979) noted the maximum useful length of the Mackereth design was 12 m. A major drawback of the Mackereth corer is its complex design and high cost of construction. The second method of penetrating sediments involves the use of a hammer. Digerfeldt (1978) designed a simple 5 m continuous corer that utilized a 15 kg hammer.

There are two problems associated with long continuous corers. Firstly, corers become less portable and more awkward with increasing casing length. Secondly, the force required to penetrate and extract a corer increases proportionately with the length of casing used. Hvorslev (1949) noted the penetration resistance was dependent on the sediment density and consistency, the corer's area ratio, smoothness of surfaces, and the shape of and clearance of the cutting shoe. The area ratio is calculated the following formula:

$$1 - \frac{\text{area of casing or liner(inside diameter)}}{\text{area of casing (outside diameter)}}$$

The area ratio represents the amount of material displaced laterally when the corer is forced in the sediment. Hvorslev (1949) suggests that ratio should be less than 10 percent, but notes higher ratios can be tolerated when the corer uses a stationary piston and a cutting shoe with a very long taper. The use of liners within the casing increases the area ratio, which decreases instrument penetration.

3. NEW CORER DESIGN

The Mackereth corer, using the modifications outlined by Barton and Burton (1979), would have been the best corer to obtain a 12 m core from Langford Lake. However, a corer of that sophistication was not locally available and could not be constructed within a modest budget.

The corer used on Langford Lake was designed to be inexpensive, portable, simple to construct and operate, and able to obtain complete sediment stratigraphy in a range of water and sediment depths, while minimizing distortion of the stratigraphy. The corer can be assembled in three different versions, depending on the depth of sediment. The basic components of the corer (Figure 4) are described below while their specifications are listed in Table 1. The casings and hammers are Schedule 10 or 40 standard steel water pipe, and the liners are plastic potable water pipe. The steel and plastic pipes are readily available from steel and plumbing supply houses.

The casings have three key functions. Firstly, they ensure straight vertical penetration. Secondly, they mark the location of the hole so additional casings and sample liners can be inserted, producing a sequential continuous core. Thirdly, the casings eliminate stress reduction by allowing water to flow between the casing and the liner to displace the volume of core.

The steel pipes used for the casings are available in 6.4 and 10 m

Figure 4: Crossection of single casing corer (modified from McKean and Nordin, 1986).

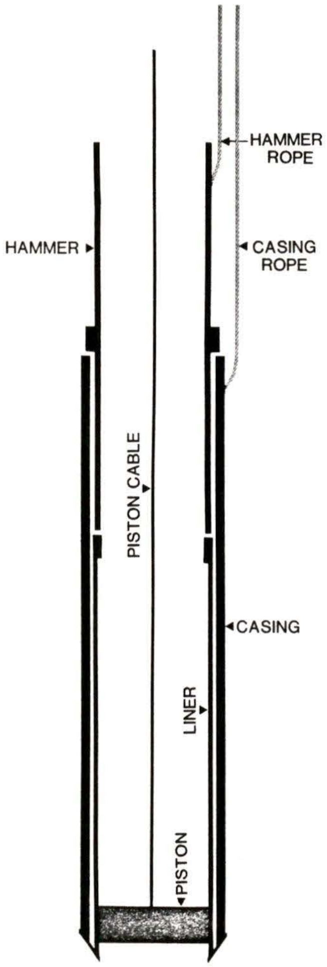

HAMMER ROPE
HAMMER
CASING ROPE
PISTON CABLE
CASING
LINER
PISTON

TABLE 1
Specifications for Corer

	Outer Casing	Inner Casing	Hammer For Outer Casing	Hammer For Inner Casing	Liner For Outer Casing	Liner For Inner Casing	Overall Length of Corer (m)
Schedule	40	40	40	40	-	-	10-15 corer
Inside Diameter (cm)	6.3	5.2	5.2	4.1	5.5	4.4	
Outside Diameter (cm)	7.3	6.0	6.0	4.8	6.1	5.0	
Length (m)	7.7	9.2	6.4	6.4	4.3	4.3	
Weight (kg/m)	8.6	5.4	5.4	4.1	-	-	
Overall Weight (kg)	66.2	48.6	34.6	26.0	-	-	
Schedule	40	-	40	-	-	-	6-10 corer
Inside Diameter (cm)	6.3	-	5.2	-	5.5	-	
Outside Diameter (cm)	7.3	-	6.0	-	6.1	-	
Length (m)	6.5-10.0	-	6.4	-	4.3	-	
Weight (kg/m)	8.6	-	5.4	-	-	-	
Overall Weight (kg)	55.9-86.0	-	34.6	-	-	-	
Schedule	10	-	40	-	-	-	<6.0 corer
Inside Diameter (cm)	6.7	-	5.2	-	5.5	-	
Outside Diameter (cm)	7.3	-	6.0	-	6.1	-	
Length (m)	≦6.4	-	6.4	-	<6.0	-	
Weight (kg/m)	5.3	-	5.4	-	-	-	
Overall Weight (kg)	Dependent on length	-	34.6	-	-	-	

lengths. The schedule 40 pipe is available in lengths up 10 m. Schedule 10 pipe, which is lighter and easier to handle, is only available in 6.4 m lengths. The dimensions of the casings used for different corer lengths are summarized in Table 1.

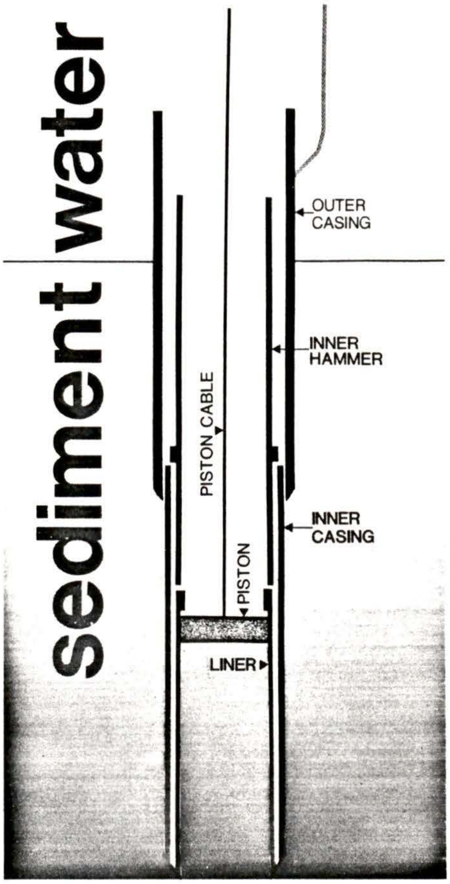
For cores less than 10 m, only one casing is required (Figure 4). The longer casings can be cut and threaded to allow easier transportation and handling. Two telescoping casings of 7.3 cm and 6.0 cm outside diameter are required for more than 10 m of penetration (Figure 5). The inner casing is 1.7 m longer (Table 1) and is not inserted into the outer casing until 7.5 m of sediment has been sampled. This casing is used to sample sediments from 7.5 to 12 m.

A cutting shoe is an important component of the corer. The shoe should have an outside diameter slightly larger (2-3%) than the casingto reduce the friction between the casing and the sediment. The shoe should also have an inside diameter smaller than the liner (0.75 - 1.5%), to minimize the friction inside the liner (Hvorslev, 1949).

Fabrication of a cutting shoe can be done simply. A 5 cm piece of pipe with an outside diameter slightly larger than the casing is placed in a lathe and tapered. The tapered end is then cut longitudinally in several places with a hack saw and hammered inward to reduce the diameter. The cutting shoe can then be spot welded onto the casing.

The hammers have two functions. The first is to prevent the liner from moving vertically in the casing while the apparatus is hammered into the sediment. Secondly, they provide the force needed to penetrate the sediments. Two sizes of hammers are required for cores greater than 10 m (Table 1). Their outside diameters are 6.0 and 4.8 cm. Both hammers are 6.4 m in length. A small metal bar is welded across the top of each hammer, where a braided nylon rope is attached. The bar must not exceed the outside diameter of the hammers.

Figure 5: Crossection of corer with two casings (modified from McKean and Nordin, 1986).

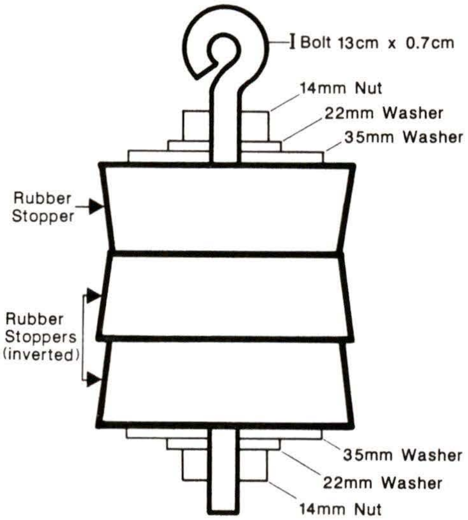

water
sediment
OUTER CASING
INNER HAMMER
PISTON CABLE
INNER CASING
PISTON
LINER

In order for the hammer to impact on the casing rather than on the plastic liner, a 2.5 cm ring of pipe of the same diameter as the casing is welded to the outside of the hammer. The location of the weld on the hammer is determined by the length of the casing and liners used (Figure 4). Considerable distortion of metal occurs at the point of impact between the hammer and casing. The distortion may reduce the inside diameter of the casing, jamming the hammer and liners. To avoid this problem a small section of a larger diameter pipe (9.7 cm ID) is welded onto the casing and the hammer to act as the point of impact.

The liners are polyethylene potable water pipe. Their inside diameters are 5.5 and 4.4 cm depending on the size of casing used and they are obtained in 6.0 m lengths. The length of the liners will be approximately 4.3 m, but will vary depending on the final specifications of the casing and hammer. The leading edge of the liner should be tapered so it fits directly behind the cutting shoe.

To assist the movement of the sediment into the liners and prevent excess sediment from entering the liner, a stationary piston is used. The pistons are constructed from numbers 8 or 10 one hole rubber stoppers, depending on the size of liners used. The pistons consist of two inverted stoppers on an eye bolt between two washers and nuts (Figure 6). A third stopper is placed at the top of the eye bolt. This stopper has 4 "V" shaped cuts to allow water to pass through into the liner as it is inserted into the casing. The cut stopper is designed to prevent water pressure from displacing the pistons from their position as the liner is inserted into the casings.

Figure 6: Crossection of piston assembly
(from McKean and Nordin, 1986).


Bolt 13cm x 0.7cm
14mm Nut
22mm Washer
35mm Washer
Rubber Stopper
Rubber Stoppers (inverted)
35mm Washer
22mm Washer
14mm Nut

The pistons are connected to an unstretchable 4.5 mm coated steel cable (clothesline wire). The cable must be sufficiently long to extend from the boat to the bottom of the core. To prevent the pistons from being pulled through the liner, a piece of smaller diameter plastic pipe is glued inside the top of each liner.

3.1 CORER OPERATION

For cores up to 10 m, only one casing is needed. The procedure for a 12 m core using 2 casings is outlined below. Similar procedures are used for corers under 10 m, but the length of the casing and number of liners vary to achieve the desired coring depth (Table 1).

The corer is assembled on site because of its awkward size and weight. The procedures outlined below are designed for 2 persons at the surface and 1 SCUBA diver (a second SCUBA diver is recommended for diving safety). First, the boat or raft must be securly positioned. Three or four anchors are required to hold the platform stationary against surface currents and wind.

Braided nylon ropes are recommended as they will not cause the casings or hammers to spin and tangle as they are raised or lowered. The rope connecting the outer casing should be looped twice around a mountaineering carabiner, and then tied to the boat. The rope will support the weight of the casing, but the loop around the carabiner will allow the casing to be lowered in a smooth controlled manner to the sediment-water interface. When the casing has been lowered to the sediment surface, the piston cable is threaded through the hammer, the first liner, and then securely attached to the pistons. Only the cut stopper on the piston is inserted into the liner. The liner and the hammer are then loaded into the casing. The piston cable is secured to the boat with no slack, while the hammer rope is left slack.

The corer is now assembled and ready for penetration. Lower the assembled corer 3.75 m using the casing rope. The hammer is used when the weight of the corer is supported by the sediments. The hammer should only be raised a maximum of 2 m, then released. Repeat until the required depth of penetration is attained.

To remove the liner, raise the hammer out of the casing. Then lift the liner out of the casing using the piston cable. When the liner reaches the surface, the piston cable is cut leaving the piston in the liner to minimize the disturbance of the surface sediments. The other end of the liner is capped before the liner and sediments are lifted into the boat.

A new liner is assembled with another piston and cable and inserted into the first casing by the SCUBA diver. The hammer is reinserted, and the piston cable secured. Coring is continued to 7.5 m. Remove the hammer and liner in the manner described above.

At this point the outer casing is almost completly imbedded in the sediments. The inner casing is lowered, using a Kellum grip, 7.5 m into the first casing, followed by the smaller diameter liner (with a piston), and hammer. The weight of the smaller casing will provide 1.0 to 1.5 m of penetration. At this point, the Kellum grip should be removed, and the smaller hammer used. When 3.5 m of sediment has been sampled, remove the hammer and liner. Insert the last liner (with a piston), load the hammer, and continue coring. The last liner will penetrate to a sediment depth of 12 m or more. The corer may not penetrate the more dense sediments (clay, sand, till etc.) underlying the organic sediments, should they be encountered.

Retrieval of the outer casing is difficult and will require mechanical winches. The inner casing (if used) is impossible to retrieve and is left in the sediment, but is buried far below the sediment-water interface and will not affect biota or lake chemistry.

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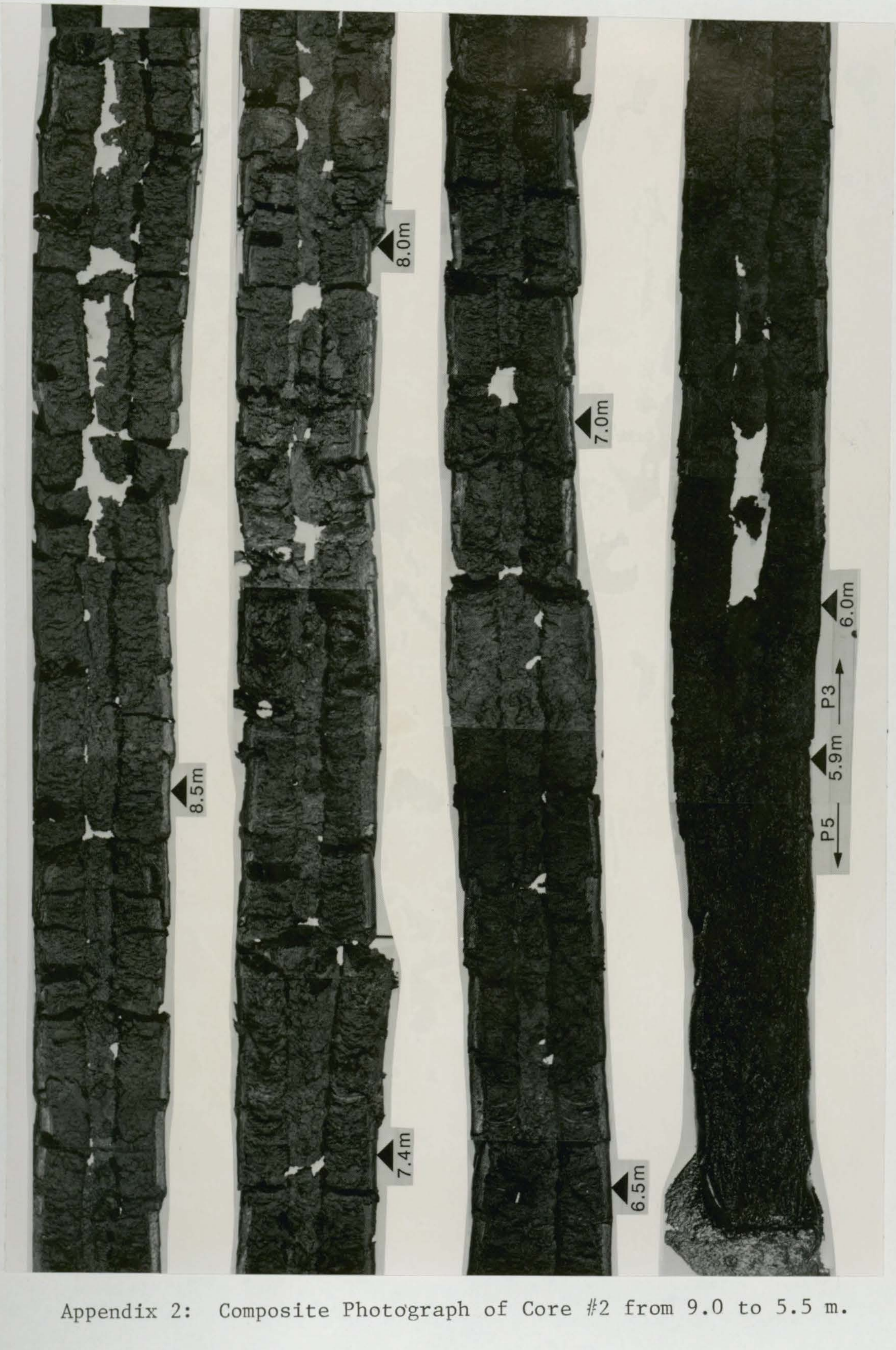
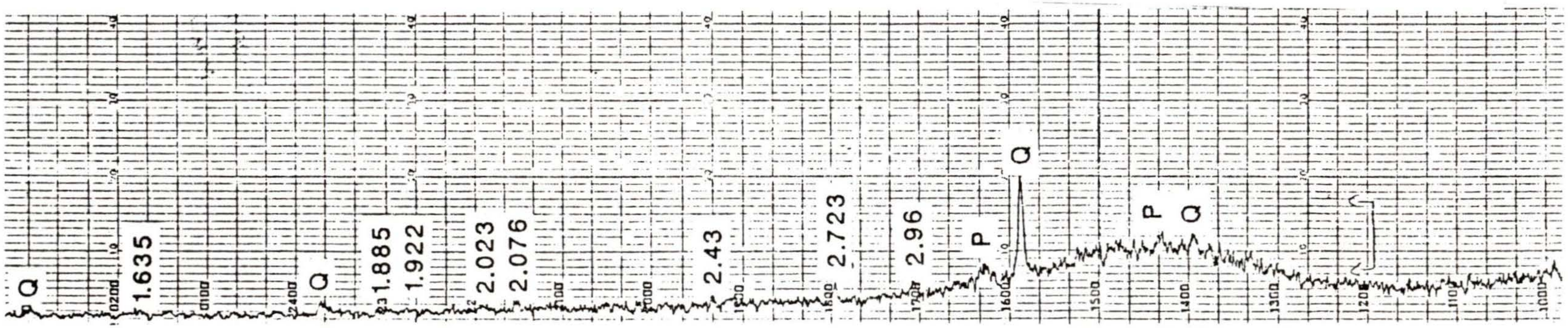
Appendix 2: Composite Photograph of Core #2 from 12.05 to 9 m.



Appendix 2: Composite Photograph of Core #2 from 9.0 to 5.5 m.

Appendix 3: X-Ray Diffraction of the Surface Sediments of Langford Lake



Q=Quartz (approx 10% of the inorganic fraction)

P=Pyrite

mostly amorphous inorganic minerals

(completed by the B.C. Ministry of Energy, Mines, and Resources)

APPENDIX 4
Surface Sediment Chemical Results From Langford Lake

SITE	ALUMINUM (mg/g)	CALCIUM (mg/g)	CARBON (mg/g)		IRON (mg/g)	LOSS ON IGNITION (%)	MAGNESIUM (mg/g)	MANGANESE (µg/g)	NITROGEN KJELDAHL (mg/g)	PHOSPHORUS (µg/g)
			Organic	Inorganic						
1	12.2	15.1	187	L0.5	25.3	42.3	2.8	800	18.7	1767
2	11.3	13.4	185	L0.5	24.0	41.3	3.1	761	18.8	1621
3	13.2	14.5	199	L0.5	24.7	43.1	3.6	708	19.2	1558
4	13.2	15.5	214	L0.5	25.8	45.1	3.9	843	19.8	1790
5	15.0	17.1	192	L0.5	17.9	42.5	4.7	137	17.5	1535
6	10.5	11.3	161	L0.5	24.0	37.1	2.7	594	16.5	1281
7	12.3	10.9	147	L0.5	25.8	35.1	3.3	489	15.6	1280
8	12.7	14.9	181	L0.5	32.7	46.6	3.7	670	19.8	1473
9	13.3	16.7	200	L0.5	38.6	42.0	4.6	601	17.7	1493
10	15.0	16.7	181	L0.5	29.1	42.0	3.5	487	17.7	1610
11	16.6	16.9	195	L0.5	30.2	42.5	3.9	673	18.2	1791
12	16.5	16.7	186	L0.5	26.1	41.5	4.2	574	17.4	1651
13	15.3	18.4	192	L0.5	14.7	40.9	4.3	135	15.6	1514
14	16.2	16.8	195	L0.5	31.0	44.3	3.6	730	19.9	1831
15	14.4	14.6	202	L0.5	28.6	44.2	3.1	788	20.5	1810
16	14.7	14.0	183	L0.5	27.7	41.3	3.1	800	18.9	1701
17	11.5	15.5	210	L0.5	24.7	44.3	2.7	701	21.3	1628
18	9.9	12.2	175	L0.5	23.1	40.4	2.3	558	18.3	1424
19	11.2	12.7	180	L0.5	23.0	40.5	2.2	566	17.9	1443
20	10.2	12.1	170	L0.5	23.1	39.9	2.4	584	17.4	1475
21	10.7	11.1	172	L0.5	26.2	38.4	2.5	571	16.9	1441
22	10.1	11.8	179	L0.5	25.0	39.4	2.3	580	17.4	1476
23	10.9	12.2	180	L0.5	25.4	39.1	2.5	546	17.4	1513
24	13.1	9.3	111	L0.5	18.8	24.3	4.4	405	11.1	1013
25	17.7	29.3	283	L0.5	30.1	60.2	4.8	1115	28.2	3015
26	13.2	22.0	258	L0.5	30.5	56.2	3.8	1146	26.4	2808
27	15.2	23.1	255	L0.5	34.2	55.9	3.9	1523	26.8	2630
28	14.2	26.3	282	L0.5	28.9	60.6	4.0	1368	27.2	2791
29	15.5	26.8	279	L0.5	35.9	59.1	4.3	1295	26.5	2616
30	15.3	24.8	260	L0.5	35.2	55.4	4.2	1300	25.7	2511
31	14.4	21.0	235	L0.5	28.3	52.1	5.0	933	22.5	1805
32	14.0	23.6	255	L0.5	33.8	55.1	4.2	957	25.7	2383
33.1	15.0	22.0	245	L0.5	33.7	53.8	4.1	971	25.9	2575
33.2	13.8	21.3	246	L0.5	32.2	52.6	4.0	962	34.5	2405
33.3	14.5	22.8	251	L0.5	34.6	53.6	4.1	976	26.2	2672
34.1	14.0	19.5	232	L0.5	36.7	51.3	4.0	839	24.5	2156
34.2	13.7	19.8	241	L0.5	36.1	51.6	4.0	838	24.4	2293
34.3	14.4	20.0	240	L0.5	35.2	51.2	4.0	836	24.4	2192

- See Figure 9 for site locations.
- Sample date - December 19, 1983.
- All results expressed on an ash free dry weight basis except LOI (%), organic carbon and Kjeldahl nitrogen (dw).

APPENDIX 5
CORE #1 - CHEMICAL RESULTS FROM LANGFORD LAKE

CORE DEPTH (m)	ALUMINUM (mg/g)	CALCIUM (mg/g)	CARBON (mg/g)		IRON (mg/g)	LOSS ON IGNITION (%)	MAGNESIUM (mg/g)	MANGANESE (µg/g)	NITROGEN KJELDAHL (mg/g)	PHOSPHORUS (µg/g)
			Organic	Inorganic						
0.68	9.2	15.7	110	< 0.5	10.5	46.7	2.3	393	16	1118
0.78	5.9	14.4	97	< 0.5	10.0	45.8	2.3	354	16	963
0.94	7.2	15.6	135	< 0.5	11.5	46.4	2.6	360	16	1057
1.08	6.1	13.7	127	< 0.5	10.2	43.6	2.4	310	15	902
1.17	5.2	11.9	109	< 0.5	8.4	40.6	2.1	276	14	745
1.24	5.7	10.8	106	< 0.5	7.9	40.3	2.2	262	14	747
1.35	5.5	11.7	124	< 0.5	8.4	37.9	2.3	267	11	752
1.55	5.5	10.8	126	< 0.5	8.4	37.0	2.1	228	12	720
1.66	5.1	10.7	130	< 0.5	8.6	37.7	2.0	247	12	727
1.75	7.1	13.3	86	< 0.5	8.9	39.9	2.2	309	13	883
1.92	8.7	12.9	104	< 0.5	11.4	37.3	2.5	304	13	933
1.97	8.2	12.8	85	< 0.5	10.7	38.6	2.5	301	13	879
2.12	7.9	12.7	107	< 0.5	10.4	37.3	2.6	299	12	759
2.22	8.0	13.1	112	< 0.5	10.9	39.3	2.7	316	13	802
2.39	7.4	12.0	118	< 0.5	9.2	37.8	2.5	287	14	689
2.53	8.8	13.9	126	< 0.5	10.9	39.6	2.9	342	15	807
2.66	8.0	13.7	143	< 0.5	9.6	39.7	2.6	325	14	769
2.76	6.6	11.4	139	< 0.5	8.9	35.4	2.2	270	13	608
2.86	6.3	10.2	51	< 0.5	8.1	35.0	2.0	250	12	593
3.00	7.8	11.8	76	< 0.5	8.6	35.0	2.5	301	13	564
3.11	8.9	12.7	127	< 0.5	9.6	35.1	2.8	334	13	594
3.26	7.8	12.5	102	< 0.5	9.7	35.3	2.6	326	13	619
3.40	7.9	11.4	104	< 0.5	10.1	36.2	2.6	299	12	583
3.55	9.5	14.1	114	< 0.5	11.8	43.7	3.0	376	10	689
3.62	8.5	13.8	115	< 0.5	10.7	37.6	2.7	362	12	679
3.74	7.0	10.9	102	< 0.5	9.1	33.0	2.3	289	10	574
3.86	7.5	11.1	106	< 0.5	9.5	33.8	2.4	324	10	521
3.90	6.8	10.0	69	< 0.5	9.1	31.5	2.3	318	10	531
4.06	8.0	10.6	105	< 0.5	9.4	33.0	2.6	338	10	556
4.18	6.7	9.5	111	< 0.5	7.9	31.1	2.3	309	10	467
4.34	6.9	11.0	98	< 0.5	9.4	34.6	2.7	376	10	527
4.58	6.8	10.3	105	< 0.5	9.7	34.3	2.5	365	10	455
4.74	7.9	12.5	99	< 0.5	11.1	39.4	2.9	443	11	595
4.89	6.9	10.7	120	< 0.5	9.8	32.5	2.6	373	11	528
5.07	8.3	12.2	105	< 0.5	12.6	37.0	2.9	466	12	604
5.21	6.9	10.6	126	< 0.5	10.2	34.8	2.4	415	11	509
5.33	6.3	9.9	105	< 0.5	10.2	34.4	2.0	391	10	509
5.48	4.9	9.6	122	< 0.5	8.6	32.4	1.7	344	10	415
5.66	4.5	9.3	110	< 0.5	8.4	32.6	1.5	367	10	439
5.85	7.0	10.4	125	< 0.5	12.2	33.0	1.9	423	11	477
5.97	6.9	11.8	114	< 0.5	14.2	40.2	2.5	518	12	483
6.19	6.0	11.1	101	< 0.5	13.6	37.9	2.1	470	11	446

- Location: Site 1 (Figure 9).
- Sample date - August 14, 1982.
- All results expressed on an ash free dry weight basis except LOI (%), organic carbon and Kjeldahl nitrogen (dw).

APPENDIX 5 (Continued)
CORE #1 - CHEMICAL RESULTS FROM LANGFORD LAKE

CORE DEPTH (m)	ALUMINUM (mg/g)	CALCIUM (mg/g)	CARBON (mg/g)		IRON (mg/g)	LOSS ON IGNITION (%)	MAGNESIUM (mg/g)	MANGANESE (μg/g)	NITROGEN KJELDAHL (mg/g)	PHOSPHORUS (μg/g)
			Organic	Inorganic						
6.34	5.5	9.9	89	< 0.5	12.5	36.3	1.9	430	11	439
6.52	6.9	11.7	145	< 0.5	14.2	39.3	2.4	522	12	467
6.71	5.9	9.7	110	< 0.5	10.9	34.2	2.2	460	10	401
6.76	6.2	10.2	109	< 0.5	11.9	35.4	2.3	492	11	504
6.96	7.1	11.9	144	< 0.5	14.0	39.5	2.3	600	13	535
7.18	6.9	11.4	97	< 0.5	13.5	38.1	2.2	607	12	483
7.34	5.1	8.9	109	< 0.5	10.9	35.0	1.8	503	10	410
7.49	6.9	9.6	98	< 0.5	11.3	36.6	2.2	556	11	441

- Location: Site 1 (Figure 9).
- Sample date - August 14, 1982.
- All results expressed on an ash free dry weight basis except LOI (%), organic carbon and Kjeldahl nitrogen (dw).

APPENDIX 6
CORE #2 - CHEMICAL RESULTS FROM LANGFORD LAKE

CORE DEPTH (m)	ALUMINUM (mg/g)	CALCIUM (mg/g)	CARBON (mg/g)		IRON (mg/g)	LOSS ON IGNITION (%)	MAGNESIUM (mg/g)	MANGANESE (µg/g)	NITROGEN KJELDAHL (mg/g)	PHOSPHORUS (µg/g)
			Organic	Inorganic						
0.05	7.5	15.1	212	< 0.5	11.2	48.9	2.4	418	19.9	1203
0.10	8.2	15.0	230	< 0.5	11.2	48.2	2.4	430	20.2	1218
0.15	8.0	15.1	241	< 0.5	11.1	48.9	2.4	450	21.0	1221
0.20	8.4	15.5	222	< 0.5	11.4	49.1	2.5	461	20.9	1233
0.25	8.5	14.8	238	< 0.5	11.1	48.6	2.5	453	21.2	1178
0.30	7.8	14.7	233	< 0.5	10.8	48.7	2.5	458	20.8	1157
0.35	8.3	15.5	235	< 0.5	11.0	49.9	2.5	469	20.8	1285
0.40	8.4	15.2	228	< 0.5	11.3	49.4	2.6	474	21.0	1213
0.45	8.3	15.0	237	< 0.5	10.9	49.2	2.5	458	21.2	1175
0.50	7.7	15.3	238	< 0.5	10.8	49.6	2.5	468	21.6	1240
0.55	7.9	14.8	235	< 0.5	10.8	49.5	2.5	463	21.0	1221
0.60	8.0	14.9	231	< 0.5	10.9	49.3	2.5	463	21.0	1270
0.65	5.5	12.4	226	< 0.5	9.8	49.4	2.1	436	21.4	1179
0.70	6.2	13.8	227	< 0.5	10.3	50.2	2.2	447	20.9	1339
0.75	5.3	11.6	234	< 0.5	10.3	51.3	2.0	396	21.0	1100
0.80	5.3	11.6	214	< 0.5	9.3	48.5	1.9	378	19.4	1089
0.85	5.4	12.6	236	< 0.5	10.4	50.6	2.0	417	20.5	1184
0.90	6.0	12.7	234	< 0.5	11.0	51.0	2.2	412	20.9	1157
0.95	5.0	11.0	223	< 0.5	8.7	47.6	1.8	337	18.7	1000
1.00	4.9	10.1	216	< 0.5	8.6	45.0	1.7	312	17.5	896
1.05	4.9	10.6	217	< 0.5	8.9	45.7	1.8	327	18.2	911
1.10	4.2	8.6	202	< 0.5	7.7	43.7	1.6	280	17.2	792
1.15	4.7	10.3			8.7	46.6	1.7	305	18.7	891
1.20	5.2	11.3			8.9	48.1	1.8	333	19.3	944
1.25	6.3	11.9			11.2	49.0	2.1	356	19.7	1062
1.30	5.7	9.4			9.6	45.5	2.0	315	18.2	930
1.35	5.1	8.8			8.3	43.1	1.8	272	17.1	804
1.40	4.2	8.4			7.3	41.8	1.6	257	16.4	728
1.45	4.1	8.0			7.0	41.6	1.6	244	16.1	719
1.50	3.9	7.3			6.5	39.9	1.6	227	16.3	650
1.85	6.0	10.9	178	< 0.5	8.3	39.2	2.0	268	15.5	929
1.90	6.4	11.3	181	< 0.5	8.3	39.8	2.0	280	15.5	930
1.95	6.4	12.5	177	< 0.5	9.3	39.5	2.0	299	17.1	966
2.00	6.0	10.5	157	< 0.5	8.1	37.9	1.8	260	15.2	877
2.20	7.5	15.1	211	< 0.5	11.2	47.2	2.3	380	20.5	1159
2.40	6.3	11.2	178	< 0.5	9.4	39.3	2.1	283	16.7	841
2.60	6.7	11.6	183	< 0.5	10.9	42.7	2.4	315	17.8	916
2.80	7.3	12.5	189	< 0.5	10.3	42.7	2.6	335	17.2	897
3.05	6.7	11.1	153	< 0.5	9.7	36.4	2.2	297	13.6	737
3.20	6.4	10.5	163	< 0.5	10.9	36.7	2.2	292	13.9	720
3.40	6.2	10.6	170	< 0.5	11.6	36.6	2.1	291	13.8	728
3.60	6.7	11.5	163	< 0.5	8.9	37.1	2.2	305	14.2	759

- Location: Site 1 (Figure 9).
- Sample date - August 25, 1983.
- All results expressed on an ash free dry weight basis except LOI (%), organic carbon and Kjeldahl nitrogen (dw).

APPENDIX 6 (Continued)
CORE #2 - CHEMICAL RESULTS FROM LANGFORD LAKE

CORE DEPTH (m)	ALUMINUM (mg/g)	CALCIUM (mg/g)	CARBON (mg/g)		IRON (mg/g)	LOSS ON IGNITION (%)	MAGNESIUM (mg/g)	MANGANESE (µg/g)	NITROGEN KJELDAHL (mg/g)	PHOSPHORUS (µg/g)
			Organic	Inorganic						
3.80	7.6	12.6	161	< 0.5	9.9	36.6	2.4	337	13.8	782
4.00	7.5	10.9	153	< 0.5	9.3	36.3	2.3	302	13.8	700
4.20	6.9	10.6	167	< 0.5	9.2	36.7	2.3	306	13.4	695
4.40	6.8	10.8	149	< 0.5	10.0	36.3	2.3	312	13.1	697
4.60	6.9	11.4	149	< 0.5	10.1	36.2	2.3	344	12.9	689
4.80	6.8	10.8	133	< 0.5	8.6	34.9	2.2	324	12.5	615
5.00	6.6	9.7	143	< 0.5	8.0	33.6	2.2	320	11.9	585
5.20	7.4	11.8	154	< 0.5	10.8	36.7	2.6	398	13.4	674
5.40	6.8	10.5	156	< 0.5	9.7	35.9	2.3	361	13.3	655
7.00	6.2	11.8	197	< 0.5	15.0	41.5	2.2	586	15.5	623
7.20	4.7	8.8	151	< 0.5	11.1	34.1	1.5	432	12.9	509
7.40	6.9	9.6	154	< 0.5	12.3	33.2	2.2	495	12.6	502
7.60	5.3	8.7	149	< 0.5	10.1	32.5	1.8	463	11.7	462
7.80	6.9	10.2	164	< 0.5	12.7	37.2	2.2	570	13.8	554
8.00	7.4	12.4	196	< 0.5	15.2	41.4	2.2	687	15.7	643
8.20	7.7	12.8	194	< 0.5	14.2	42.0	2.3	739	16.0	655
8.40	8.1	11.5	161	< 0.5	16.5	37.7	2.3	703	14.3	598
8.60	5.8	10.0	173	< 0.5	11.8	37.4	1.8	653	14.2	503
8.80	7.5	9.4	156	< 0.5	12.1	34.7	2.2	634	13.1	500
9.00	9.0	10.6	180	< 0.5	14.4	38.1	2.7	756	14.8	579
9.15	12.4	10.8	157	< 0.5	25.1	35.9	3.6	812	14.1	687
9.30	10.6	10.2	169	< 0.5	21.6	36.3	3.4	767	14.3	678
9.50	19.8	9.4	113	< 0.5	36.6	26.3	6.6	780	10.2	762
9.70	16.0	9.3	130	< 0.5	25.9	28.2	6.8	816	10.6	782
9.80	11.2	12.0	195	< 0.5	19.0	39.7	3.2	877	15.6	787
9.90	4.1	3.4	46	< 0.5	4.5	13.7	0.8	229	4.8	359
10.00	16.6	16.6	235	< 0.5	35.8	46.4	5.6	1350	18.2	1175
10.10	14.4	16.3	246	< 0.5	27.1	49.6	5.0	1289	18.9	1132
10.30	14.5	16.9	251	< 0.5	34.5	50.2	5.4	1397	18.9	1140
10.50	13.6	16.8	261	< 0.5	29.8	52.1	5.3	1461	19.6	970
10.70	14.2	17.9	263	< 0.5	29.2	52.8	5.3	1561	20.1	993
10.90	16.4	20.6	287	< 0.5	36.6	56.1	6.3	1794	21.8	1218
11.10	17.4	19.7	280	< 0.5	34.8	55.2	6.6	1703	22.4	1198
11.30	15.1	15.6	240	< 0.5	42.0	48.2	7.1	1474	19.8	1117
11.50	14.8	13.7	209	< 0.5	32.4	41.7	7.5	1341	16.7	1216
11.60	16.6	12.6	188	< 0.5	46.9	38.0	9.0	1451	15.0	1035
11.70	19.2	13.0	178	< 0.5	49.4	37.1	9.6	1305	13.9	1063
11.75	21.7	11.4	157	< 0.5	43.8	33.2	10.1	1416	12.1	943
11.80	19.7	10.3	146	< 0.5	48.9	31.8	9.9	1612	11.3	831
11.90	28.3	8.8	77	< 0.5	55.8	17.7	14.4	1312	5.8	860
12.00	21.4	9.8	134	< 0.5	59.0	30.0	11.4	1311	10.1	861
12.05	32.2	8.4	15	< 0.5	48.7	6.6	17.2	1252	1.4	832

- Location: Site 1 (Figure 9).
- Sample date - August 25, 1982.
- All results expressed on an ash free dry weight basis except LOI (%), organic carbon and Kjeldahl nitrogen (dw).

VITA

Surname: McKean Given Names: Colin John Pearce

Place of Birth: Victoria, B. C. Date of Birth: September 21, 1955

Educational Institutions Attended, with Dates of Entering and Leaving

UNIVERSITY OF VICTORIA, VICTORIA, B.C.	1973 to 1977
UNIVERSITY OF VICTORIA, VICTORIA, B.C.	1981 to 1987

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Title of Thesis

THE PHYSICAL AND CHEMICAL DESCRIPTION OF THE LIMNETIC SEDIMENTS FROM

LANGFORD LAKE, SOUTH VANCOUVER ISLAND, BRITISH COLUMBIA

Author [redacted]

Signature

COLIN J.P. MCKEAN

Name

Dec 30/1987

Date