

An Investigation of Geological and Geochemical Characteristics  
of Late-Quaternary Sediments in the Georgian Bay Region,  
Southern Ontario

by

Chang-Sen Chen

A thesis submitted to the Department of Geological Sciences  
in partial fulfilment of the requirements  
for the degree of  
Master of Science

BROCK UNIVERSITY  
ST. CATHARINES, ONTARIO

September, 1980

© Chang-Sen Chen

## ABSTRACT

Core samples of postglacial sediments and sediment surface samples from Shepherd Lake on the Bruce Peninsula, Harts Lake on the Canadian Shield, and two cores from Georgian Bay (core P-1 in the western deep part and core P-7 in the eastern shallow part) have been analyzed for pH, grain size distribution, water content, bulk density, loss on ignition at  $450^{\circ}\text{C}$  and  $1100^{\circ}\text{C}$ , major oxides ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\Sigma\text{FeO}$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$ ,  $\text{TiO}_2$ ,  $\text{MnO}$  and  $\text{P}_2\text{O}_5$ ) and trace elements (Ba, Zr, Sr, Y, S, Zn, Cu, Ni, Ce and Rb).

The sediment in Georgian Bay are generally fine grained (fine silt to very fine silty clay) and the grain size decreases from the Canadian Shield (core P-7) towards the Bruce Peninsula (core P-1) along the assumed direction of sediment transport. This trend coincides with a decrease in sorting coefficient and an increase in roundness. Other physical characteristics, such as water content, bulk density and loss on ignition are positively correlated with the composition of sediments and their compaction, as well as with the energy of the depositional environment.

Analyses of sediment surface samples from Shepherd Lake and Harts Lake indicate the influence of bedrock and surficial deposits in the watershed on pH condition that is also influenced by the organic matter content and probably by

man's activities. Organic matter content increases significantly in the surface sediment in these small lakes as a result of either natural eutrophication or anthropogenic organic loading. The extremely high organic matter content in Shepherd Lake sediment indicates rapid natural eutrophication in this closed basin and high biological productivity during postglacial time, probably due to high nutrient levels and shallow depth.

The chemical composition of the Canadian Shield bedrock is positively correlated with the chemical characteristics of predominantly inorganic lake sediments that were derived from the Shield rocks by glacial abrasion and by postglacial weathering and erosion of both bedrock and surficial deposits. High correlation coefficients were found between organic matter in lake sediments and major oxides ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\Sigma\text{FeO}$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{K}_2\text{O}$  and  $\text{MnO}$ ), as well as some trace elements (Ba, Y, S, Zn, Cu, Ni and Rb).

The chemical composition of sediments in Harts Lake and core P-7 in Georgian Bay on the Canadian Shield differs from the chemistry of sediments in Shepherd Lake and core P-1 in Georgian Bay on the Bruce Peninsula. The difference between cores P-1 and P-7 is indicated by values of  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\Sigma\text{FeO}$ ,  $\text{MgO}$ ,  $\text{CaO}$ , Ba, Zr, Sr, Y and S, and also by the organic matter content.

This study indicates that the processes of sediment transport, depositional environment, weathering of the rocks and surficial deposits in the watershed, as well as chemical composition of source rocks all affect the chemical characteristics of lake sediments.

The stratigraphic changes and variations in lake sediment chemistry with regard to major oxides, trace elements, and organic matter content are probably related to the history of glacial and postglacial lake stages of the Georgian Bay Region and, therefore, the geochemical data can make a useful contribution to a better understanding of the Late-Quaternary history of the Great Lakes.

## ACKNOWLEDGEMENTS

The author wishes to thank Dr. J. Terasmae for suggesting the thesis topic and Dr. E. Miryneck and Dr. P. A. Peach for their review and critical comments of the thesis manuscript. The author also wishes to thank Dr. W. T. Jolly for his helpful suggestion and advice during the chemical analysis by XRF. Dr. W. A. Glosschenko at CCIW was thanked for his review of the geochemistry in this study. Discussions with other faculty members of the Department of Geological Sciences were also invaluable.

The author is indebted to Mr. T. W. Wu who helped with the computer programming in the grain-size distribution analysis. Also, many thanks to the graduate students of the Department of Geological Sciences at Brock University who were helpful in their discussion and suggestion. Mrs. Jane Bee-Sin Chen, the author's wife, is thanked for her striving assistance in typing the thesis and drafting the illustrations.

Dr. J. Terasmae is thanked again for his tireless sacrifice for correcting the draft, helping with writing and stimulating some sparkling ideas. By these, the author will remember always.

# TABLE OF CONTENTS

	Page
ABSTRACT . . . . .	iii
ACKNOWLEDGEMENTS . . . . .	vi
TABLE OF CONTENTS . . . . .	vii
LIST OF TABLES . . . . .	x
LIST OF FIGURES . . . . .	xii
INTRODUCTION . . . . .	1
Object of Research . . . . .	1
Previous Work . . . . .	2
STUDY AREAS . . . . .	6
Location . . . . .	6
Bedrock Geology . . . . .	11
Quaternary Geology . . . . .	13
Quaternary lake stages in Georgian Bay and the Lake Huron Basin . . . . .	15
Characteristics of physiography and glacial deposits . . . . .	18
Soil Formation, Soil Types and its Relation to Glacial Deposits . . . . .	20
Climate . . . . .	24
General Description of the Lake Bottom Sediments .	26
SEDIMENT SURVEY AND LABORATORY METHODOLOGY . . . . .	32
Sampling . . . . .	32
Subsampling . . . . .	34
Analytical Techniques . . . . .	36

	page
SEDIMENTOLOGY OF THE LAKE SEDIMENTS . . . . .	38
Grain Size of the Sediment and Depositional Environment . . . . .	38
Sediment Size Analysis . . . . .	41
Comparison of Sediment Characteristics . . . . .	43
Stratigraphic Comparison . . . . .	47
PHYSICAL CHARACTERISTICS OF LAKE SEDIMENTS . . . . .	53
Results of Analysis . . . . .	53
Discussion and Correlation of Average Values . . . . .	54
Stratigraphic Correlation . . . . .	60
GEOCHEMISTRY OF THE LAKE SEDIMENTS . . . . .	69
Some Limnological Comparisons between Harts Lake and Shepherd Lake . . . . .	69
Geochemistry of Major oxides . . . . .	74
Results . . . . .	74
Comparison of average-valued major oxides from P-1,P-7,H-1 and S-1 . . . . .	76
Stratigraphic distribution of individual major oxides . . . . .	82
The relationship between the bedrock and the major oxides . . . . .	89
Relationship between individual major oxides . . . . .	95
Relationship between major oxides and organic matter . . . . .	103
Geochemistry of Trace elements . . . . .	109
Results . . . . .	109
Interpretation of the results . . . . .	114
Geochemistry of Sulphur . . . . .	125

DISCUSSION	. . . . .	page 132
SUMMARY AND CONCLUSIONS	. . . . .	140
RECOMMENDATIONS	. . . . .	144
SELECTED BIBLIOGRAPHY	. . . . .	146
APPENDIX I	. . . . .	156
APPENDIX II	. . . . .	159
APPENDIX III	. . . . .	163
APPENDIX IV	. . . . .	168
APPENDIX V	. . . . .	170
APPENDIX VI	. . . . .	178



# LIST OF TABLES

Table		Page
1	A classification of Soils:Orders, Suborders, Great Soil Group, and Subgroup (Modified from Richards,1961; and Buckman and Brady,1969) . .	22
2	Sand, silt, and clay contents of the Upper Great Lakes and Harts Lake, Canadian Shield . .	45
3	The values of mean, median, and standard deviation (correlation coefficient) of cores P-1,P-7, and H-1 . . . . .	51
4	Average values of some physical properties of P-1,P-7,H-1, and S-1 cores . . . . .	55
5	Values of water contents, bulk densities, and measurements of loss on ignition at two different temperatures of four cores' samples .	68
6	Limnological comparisons between Harts Lake and Shepherd Lake . . . . .	70
7	Mean values of ten major oxides in the lake sediments of the study areas . . . . .	75
8	Recalculated values (100%) of Table 7 . . . . .	75
9	Average composition of bedrock from Canadian Shield and Bruce Peninsula . . . . .	92
10	CaO/MgO ratios of lake sediments in the study areas, and of bedrock from Canadian Shield and Bruce Peninsula (From Shaw et al.,1967;Eade and Fahrig,1971; and Liberty and Bolton,1971) . . .	94
11	Correlation coefficient matrix for major oxides in P-1 core . . . . .	96
12	Correlation coefficient matrix for major oxides in P-7 core . . . . .	96
13	Correlation coefficient matrix for major oxides in H-1 core . . . . .	97

Table		Page
14	Correlation coefficient matrix for major oxides in S-1 core . . . . .	97
15	Correlation coefficients among major oxides, organic matter, and clay-size fraction . . . .	105
16	The ranges and mean values of trace elements concentrations in the lake sediments . . . . .	110
17	Correlation coefficient matrix for trace elements in H-1 core . . . . .	117
18	Correlation coefficient matrix for trace elements in P-1 core . . . . .	118
19	Correlation coefficient matrix for trace elements in P-7 core . . . . .	119
20	Correlation coefficients between trace elements and organic matter . . . . .	124

## LIST OF FIGURES

Figure		Page
1	Location of study areas and the coring sites in Georgian Bay . . . . .	7
2	Location map of Harts Lake . . . . .	9
3	Location map of Shepherd Lake and bedrock geology of Wiarton area, Bruce Peninsula (After Liberty and Bolton, 1971) . . . . .	10
4	Bedrock stratigraphy cross sections of Georgian Bay, Bruce Peninsula, and Canadian Shield . . . . .	12
5	Bathymetry of Georgian Bay . . . . .	14
6	The distribution of Georgian Bay surface bottom sediments (After Sly and Thomas, 1974) .	28
7	Six depositional basins of Georgian Bay (From Kemp and Harper, 1977) . . . . .	28
8	Stratigraphic variations of clay percentage (%) of cores P-1, P-7, and H-1 versus depth(m)	48
9	Relationship between porosity and median diameter of sediment particles (Modified from Meade, 1966) . . . . .	56
10	Relationship between porosity and mean grain size . . . . .	56
11	Relation between water content(% , as an equiva- lent of porosity) and bulk density( $\text{g}/\text{cm}^3$ ) of P-1, P-7, H-1, and S-1 cores . . . . .	58
12	Stratigraphic variations of water content (weight %) and bulk density( $\text{g}/\text{cm}^3$ ) of P-7, H-1, and S-1 cores . . . . .	61
13	Two loss on ignition measurement of P-1, P-7, H-1, and S-1 cores(L.O.I. is in weight %). .	62

Figure		Page
14	Bathymetry map and location of surface bottom samples of Harts Lake . . . . .	72
15	Location of surface bottom samples of Shepherd Lake . . . . .	72
16	Stratigraphic variations of major oxides versus depth(cm) of P-1 . . . . .	83
17	Stratigraphic variations of major oxides versus depth(cm) of P-7 . . . . .	84
18	Stratigraphic variations of major oxides versus depth(cm) of core H-1 . . . . .	85
19	Contents of major oxides vs. depth(cm) of core S-1 . . . . .	86
20	Relationship of $TiO_2$ vs. $K_2O$ , $Al_2O_3$ vs. $K_2O$ , $FeO$ vs. $MgO$ and $Al_2O_3$ vs. $MgO$ in P-1 and P-7 cores .	101
21	Relationship of $Al_2O_3$ vs. $SiO_2$ , $K_2O$ vs. $TiO_2$ , $Al_2O_3$ vs. $FeO$ and $CaO$ vs. $MgO$ in H-1 and S-1 cores .	102
22	Stratigraphic variations of trace elements versus depth(cm) of core P-1 . . . . .	111
23	Stratigraphic variations of trace elements versus depth(cm) of core P-7 . . . . .	112
24	Stratigraphic variations of trace elements versus depth(cm) of core H-1 . . . . .	113
25	Stratigraphic variations of sulphur versus depth(m) . . . . .	127

## INTRODUCTION

### Object of Research

The Great Lakes of North America which lie on the Canada-U.S.A. border, collectively comprise about 240,000 Km<sup>2</sup>, the largest freshwater body on earth. Among the Great Lakes, Georgian Bay has a surface area of 14,000 Km<sup>2</sup> and is considered as part of Lake Huron. The Bay is entirely within Canada and relatively little research on it has been carried out. This study was planned to obtain more data in physical, chemical and sedimentological aspects of the lacustrine environment in order to expand the research on Georgian Bay. In addition, a correlation of data obtained with those from other Great Lakes will also be attempted.

Although research on lacustrine sediments has lagged behind the studies of marine sediments for more than a decade, work on sediments of the Great Lakes has increased rapidly in recent years due to concerns expressed by society in respect to environmental problems. Geochemical studies of lake sediments in the Great Lakes Region have been concerned chiefly with problems of pollution and deposition since settlement by Europeans. Some studies have been made of sediments in small lakes similar to those carried out on sediments in this study, i.e. Shepherd Lake on the Bruce Peninsula and Harts Lake on the Canadian Shield. In Georgian Bay, geochemical studies have been made of surface bottom sediments, and this research was planned to extend such studies

to include the whole of the postglacial time. The following objectives were defined:

- 1) To use the content of major oxides and the concentration of trace elements for comparing sediments with probable bedrock source.
- 2) To determine the origin and type of the depositional environment from an analysis of the physical characteristics of the lacustrine sediments.
- 3) To determine aspects of the sedimentary history of the deposits studied, by grain size analysis.
- 4) To obtain the stratigraphic correlation of sediment records from Georgian Bay, Harts Lake and Shepherd Lake.
- 5) To investigate the relationship among major oxides, trace elements and organic matter with the view to deciphering the history of deglaciation in the study areas.
- 6) To evaluate man's impact on the sediment records in the lakes studied.

#### Previous Work

Little detailed research had been undertaken on the Great Lakes sediments until about 1960. Hough (1958) systematically classified the previous research related to gravel, sand, silt and clay distribution in Lake Michigan, Lake Superior, Lake Erie and Lake Ontario. Reid (1961) investigated the bottom sediments from north and south-central Lake Michigan for grain size distribution, loss on ignition and carbonate content. Degens (1965)

in his "Geochemistry of Sediments" formulated a new concept about the sediments according to their origin and chemical properties, and classified them into four groups: i) weathering residues of igneous rock and metamorphic rock; ii) minerals of low temperature and aqueous formation; iii) mobile phases; and iv) organic constituents. One of the first studies directly related to the Great Lakes sediments' geochemistry is by Callender (1969). He studied the sediments in Lakes Michigan and Superior for bulk calcium, magnesium, iron, manganese, inorganic carbon, organic carbon and total nitrogen and suggested that the sedimentary calcium and magnesium are combined in the carbonate minerals calcite and dolomite, and that the organic matter increases significantly in the surface sediment as a result of natural eutrophication.

Scientists at CCIW (Canada Centre for Inland Waters), Burlington, Ontario, studied in the relationship of grain size, clay content, quartz and organic carbon in the sediments of Lakes Erie and Ontario (Thomas, 1969a), and the organic carbon and nitrogen in the surface sediment of Lake Ontario, Lake Erie and Lake Huron (Kemp, 1969). The distribution of feldspar in surface bottom sediments of Lake Ontario was examined by Thomas (1969b). Kemp et al. (1972) studied the changes in carbon, nitrogen, phosphorus and sulfur of Lakes Ontario, Erie and Huron, and a review of Great Lakes limnology was published by Sly and Thomas (1974).

Few published studies are specifically related to Georgian Bay sediments. Probably, one of the first studies was made by Anderson and Terasmae (1966) on the palynology of the bottom surface sediments in Georgian Bay. Sly (1969) studied the sedimentological characteristics of Georgian Bay bottom sediments north of Tobermory in Flowerpot Basin, and stated that a significant thickness of postglacial lake deposits (varved clays and muds) covers the lake floor. Anderson (1973) and CCIW staff carried out a stratigraphic coring and an acoustic profiling project in Georgian Bay. This cruise was the most detailed one to measure the bathymetry and collect surface bottom samples and core samples. Sly and Thomas (1974) discussed bottom sediment distribution and iron and manganese occurrence in the Great Lakes. That study showed that a major part of the lake bottom in Georgian Bay was covered by glaciolacustrine clays and muds, especially in the deeper central basin. Iron and manganese were found in Flowerpot Basin, French River Basin and Nottawasaga Basin, and manganese nodules were found in the areas studied by Sly (1969).

Fitchko and Hutchinson (1975) were the first to make a comparative study of heavy metal concentrations in river mouth sediments around the Great Lakes, including the rivers from Georgian Bay watersheds. They found that significant correlation existed between the heavy metal concentrations and clay content and loss on ignition (an equivalent to organic matter). McAtee (1977) studied the palynology of surface bottom samples and one 12.94 m long sediment core (P-10) from Georgian Bay, and he



investigated the sedimentation rate, sediment type, sediment origin and transportation.

The most recent study was carried out by Kemp and Harper in 1977. Using the surface bottom samples from three different areas in Georgian Bay (Flowerpot Basin, Owen Sound Trough and Nottawasaga Basin), they calculated the sedimentation rate in the local basins and showed that these rates are lower than those in the other Great Lakes.

## STUDY AREAS

### Location

Georgian Bay        Georgian Bay is part of the eastern Great Lakes Region, located between latitude  $44^{\circ}30'$  and  $46^{\circ}00'$  North and longitude  $79^{\circ}45'$  and  $82^{\circ}00'$  West and it has a surface area of about  $14,000 \text{ Km}^2$  (Fig. 1). It is oblong in shape, with the long axis trending northwest, and is about 176m a.s.l. (above sea level). The Bay basin is connected to Lake Huron by narrow channels between the Bruce Peninsula and Manitoulin Island (Thomas et al., 1973).

The eastern part of the basin is characterized by its shallow depth, controlled by bedrock of the Canadian Shield. In contrast, the western part of the basin is rather deep, dominated by the Niagara Escarpment along the east side of the Bruce Peninsula, and the deepest part of the Georgian Bay (almost 168m) is in Flowerpot Basin near this escarpment (See Fig. 4, Fig. 5 and Fig. 8).

Drainage into Georgian Bay comes primarily from Shield rivers, such as the Muskoka, Moon, French and Magnetawan Rivers etc.. East Meaford is the only significant stream draining into Georgian Bay from the Bruce Peninsula (Liberty and Bolton, 1971), and

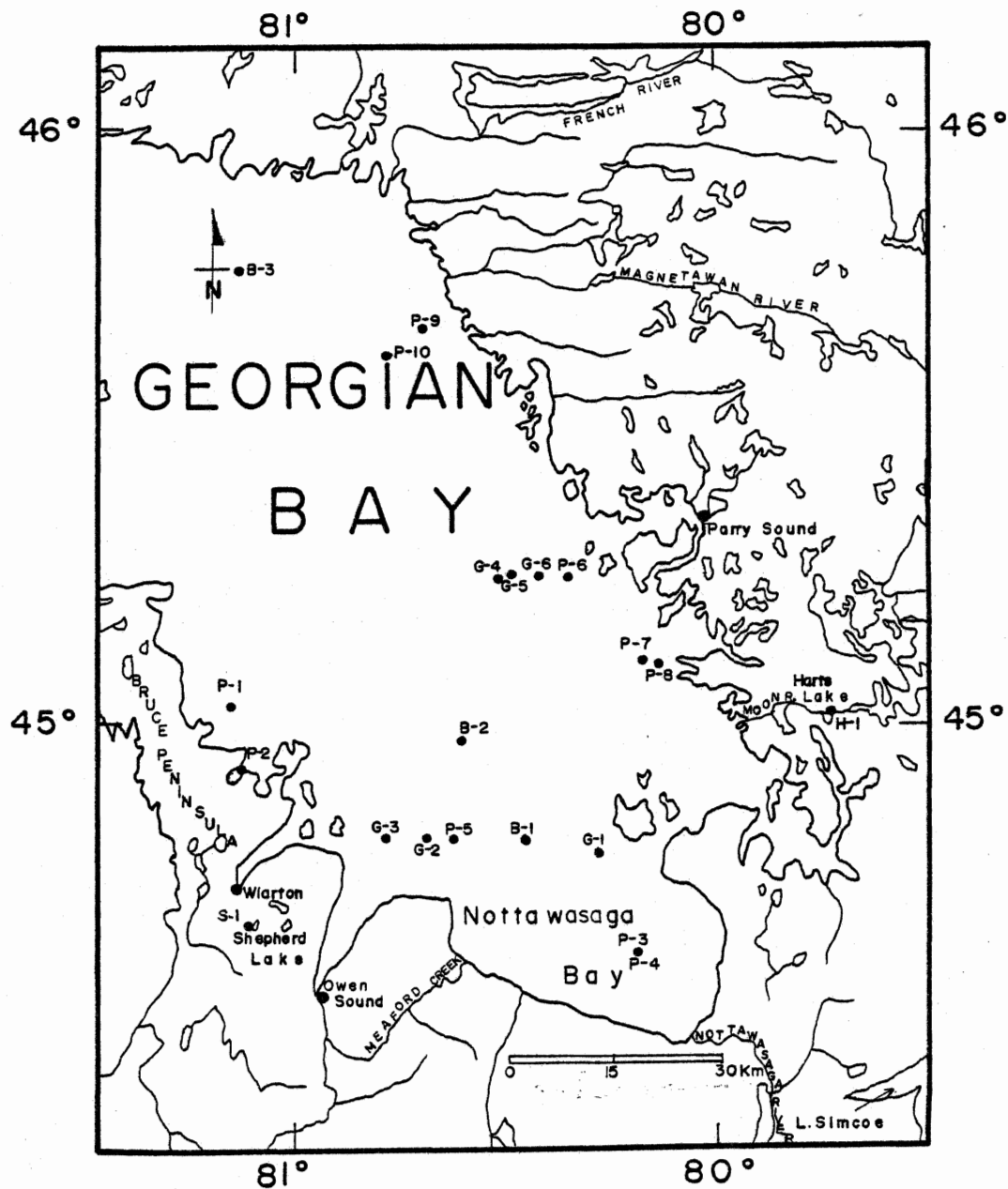


Figure 1. Location of study areas and the coring sites in Georgian Bay.

the Nottawasaga River is the only important stream from the south.

Harts Lake        This lake is situated east of Georgian Bay about 5 Km west of Bala on Highway No. 660 at latitude  $45^{\circ}04'$  and longitude  $79^{\circ}41'$  (Fig. 2). It has a surface area of almost  $7,000 \text{ m}^2$ , a mean water depth about 3.3m, and it is 244m above sea level. It is surrounded by Precambrian bedrock which is characterized locally by strongly granitized hornblende migmatite. The Moon River and Muskoka River watershed includes the lake and drain into Georgian Bay. In 1973, Highway No. 660 was re-routed to pass along the lake shore. The lake basin is composed entirely of bedrock which is mantled with thin patches of stony till.

Shepherd Lake    It is situated west of Georgian Bay on the Bruce Peninsula; latitude  $44^{\circ}40'$  and longitude  $81^{\circ}08'$  about 8.8 Km south of Wiarton (Fig. 3), and about 231m above sea level. The lake occupies a closed basin in glacial deposits without inflow or outflow by streams. It is shallow, with a mean water depth about 1m, and has a surface area about  $4,000 \text{ m}^2$ . The glacial deposits are underlain by Paleozoic bedrock which is dolomite of the Guelph Formation, Silurian in age.

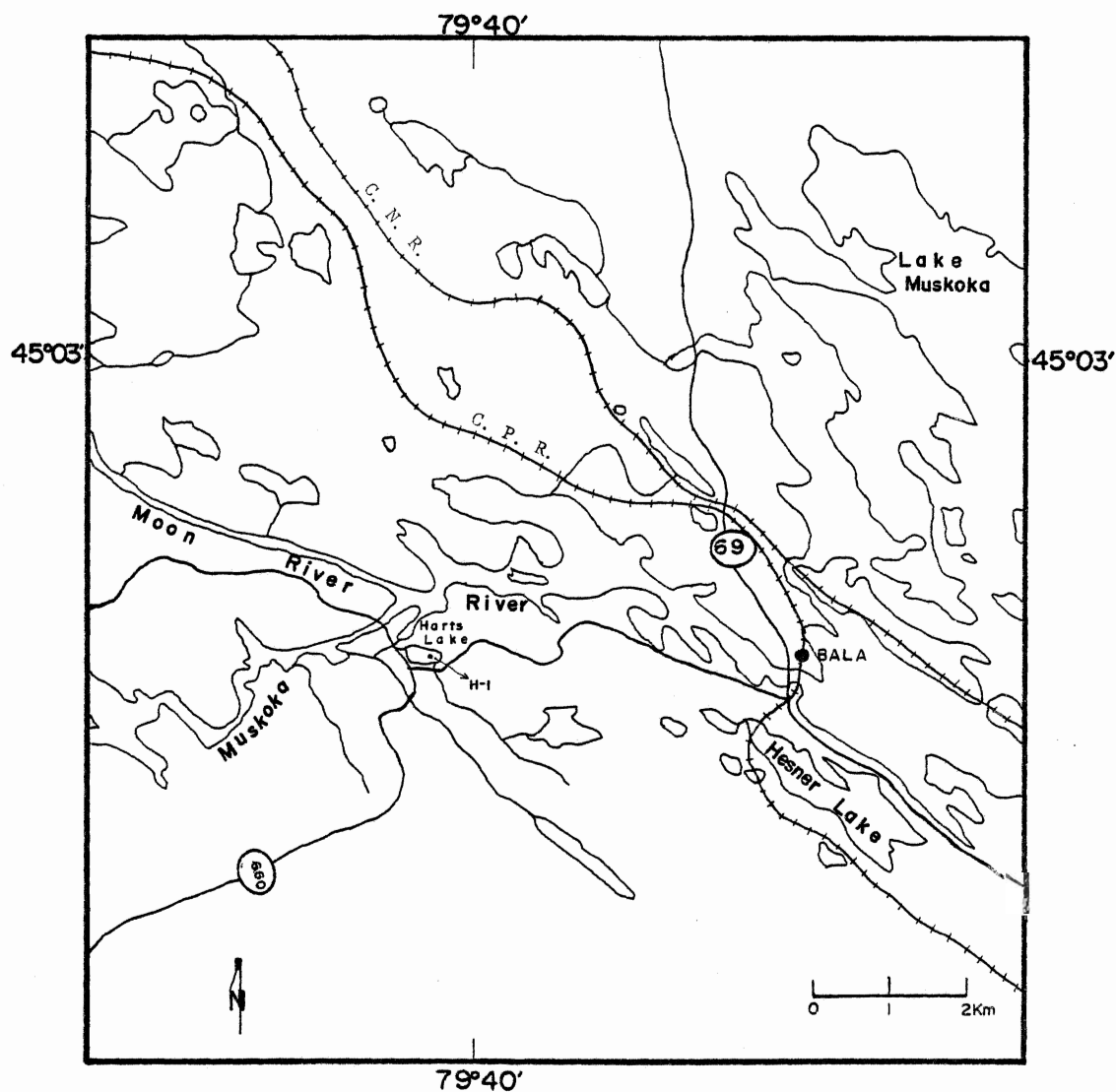


Figure 2. Location map of Harts Lake.

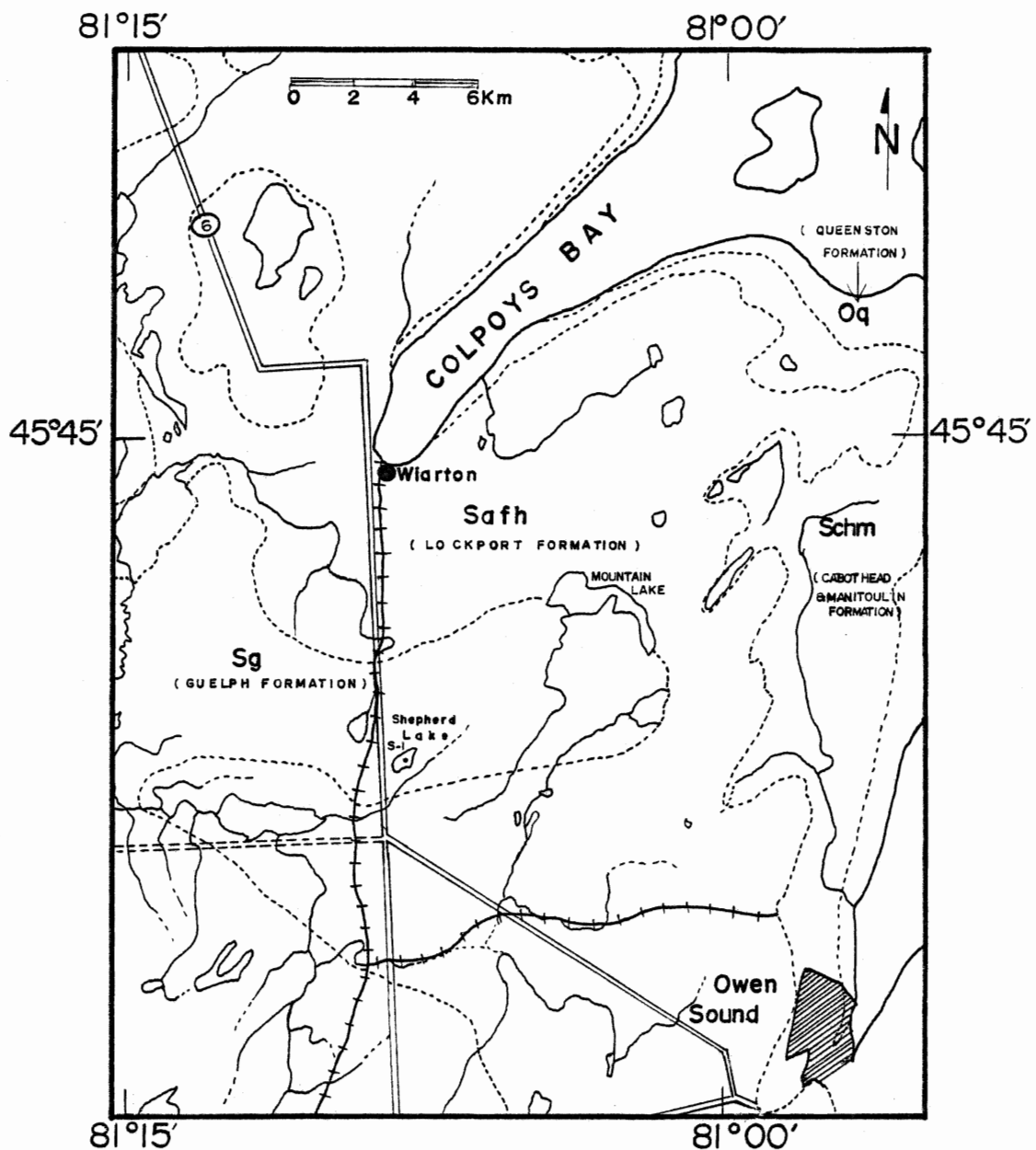


Figure 3. Location map of Shepherd Lake and bedrock geology of Wiarton area, Bruce Peninsula (After Liberty and Bolton, 1971).

## Bedrock Geology

Georgian Bay lies along the contact between the sedimentary Paleozoic rocks to the southwest and the metamorphic, sedimentary and volcanic rocks of the Canadian Shield to the east and northeast (Fig. 4). The metamorphic rocks are consistent with their probable origin as a series of continental marginal sediments and volcanic rocks both of which have been considerably folded and recrystallized. Typical rock in Harts Lake area are migmatitic gneiss, quartz feldspathic gneiss, schist and amphibolite. The amphibolite was derived from lime rich argillaceous sediments and interbedded with quartzite and marble (Hewitt, 1967), representing the equivalents of calc-argillites and calc-arenites. All these rocks were progressively metamorphosed into mica schist, hornblende gneiss or biotite gneiss.

Towards the west, Ordovician and Silurian strata on the Bruce Peninsula transgressively overlap the Precambrian bedrock (See Fig. 4). The monoclinial structure (cuesta) and low relief result in the strata dipping toward Lake Huron and the Michigan Basin at a gradient 4 m/Km (Liberty, personal comm.). The Niagara Escarpment, the most distinguishable feature in the Peninsula, extends from Manitoulin Island toward the southeast through to New York State ending around the Rochester area.

This escarpment, largely the result of differential weathering and extensive stream erosion of basal Ordovician shales and overlying Silurian dolomite, was only partly modified

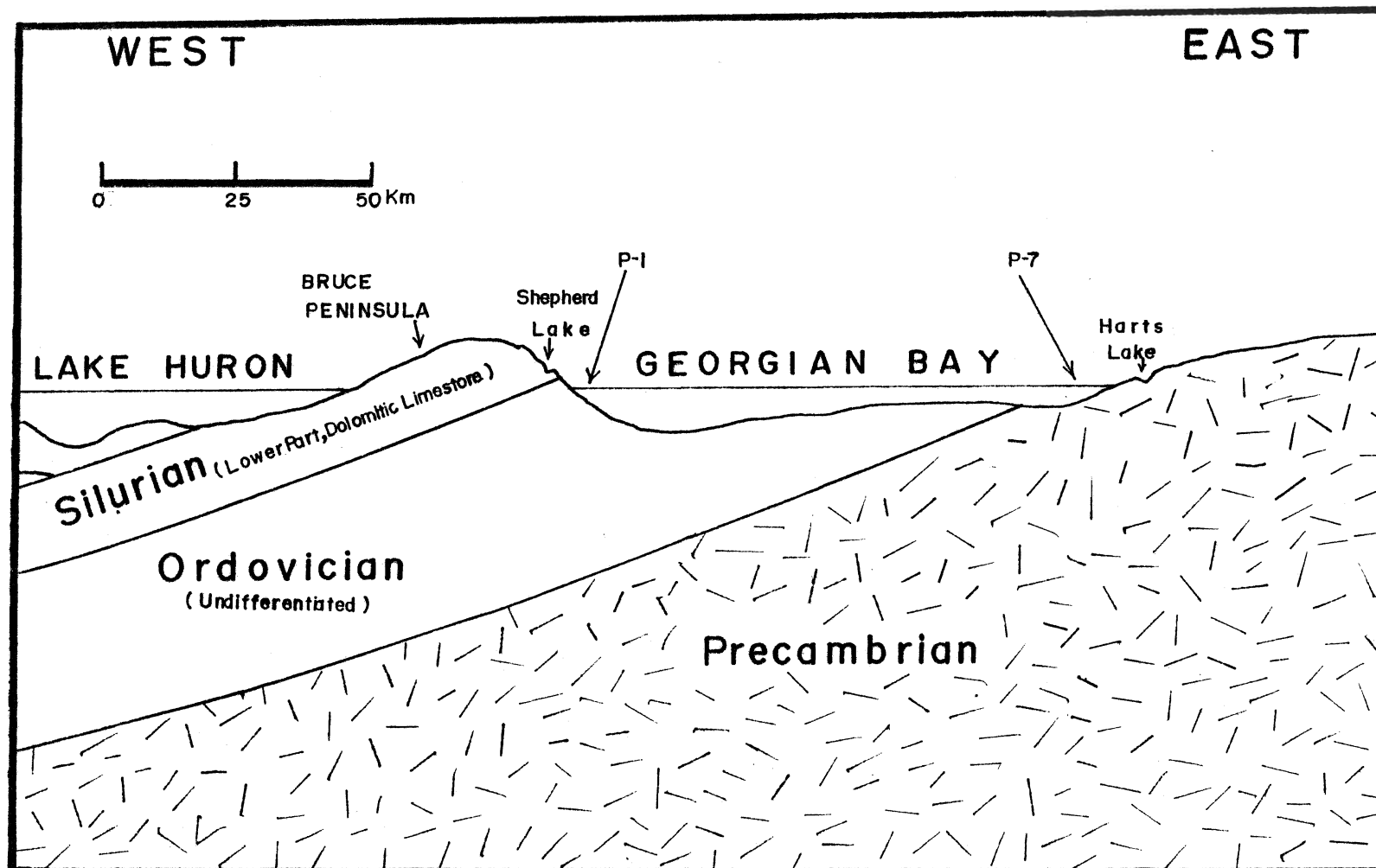


Figure 4. Bedrock stratigraphy cross sections of Georgian Bay, Bruce Peninsula, and Canadian Shield.



during the successive Pleistocene glaciations. The narrow lowland below the escarpment is underlain by Queenston shales which in turn are underlain by a substantial thickness of older Paleozoic rocks. The greatest relief along the Niagara Escarpment is about 61m with an average between 36.6m to 42.7m (Liberty and Bolton, 1971)

Shepherd Lake, situated on top of the Niagara Escarpment, is surrounded by Silurian dolomite of the Guelph Formation (Fig. 3). The bedrock, mantled by thin ground moraine, outcrops in patches near the lake basin and it is exposed in scarp faces and road cuts locally. Maximum relief in the area is about 38.5m.

The bottom topography of Georgian Bay and the topography of the Bruce Peninsula are controlled primarily by the bedrock. Bathymetrical data (Canadian Hydrographic Service, 1971) show that Georgian Bay is shallower on the east side than the west largely because of the differential resistance to stream and glacial erosion (Fig. 5).

#### Quaternary Geology

The Georgian Bay Region has a relatively continuous cover of Quaternary deposits relating to the last glaciation, and their distribution is closely controlled by the bedrock surface that has been modified by glacial erosion and deposition.

The physiographic features surrounding Georgian Bay have

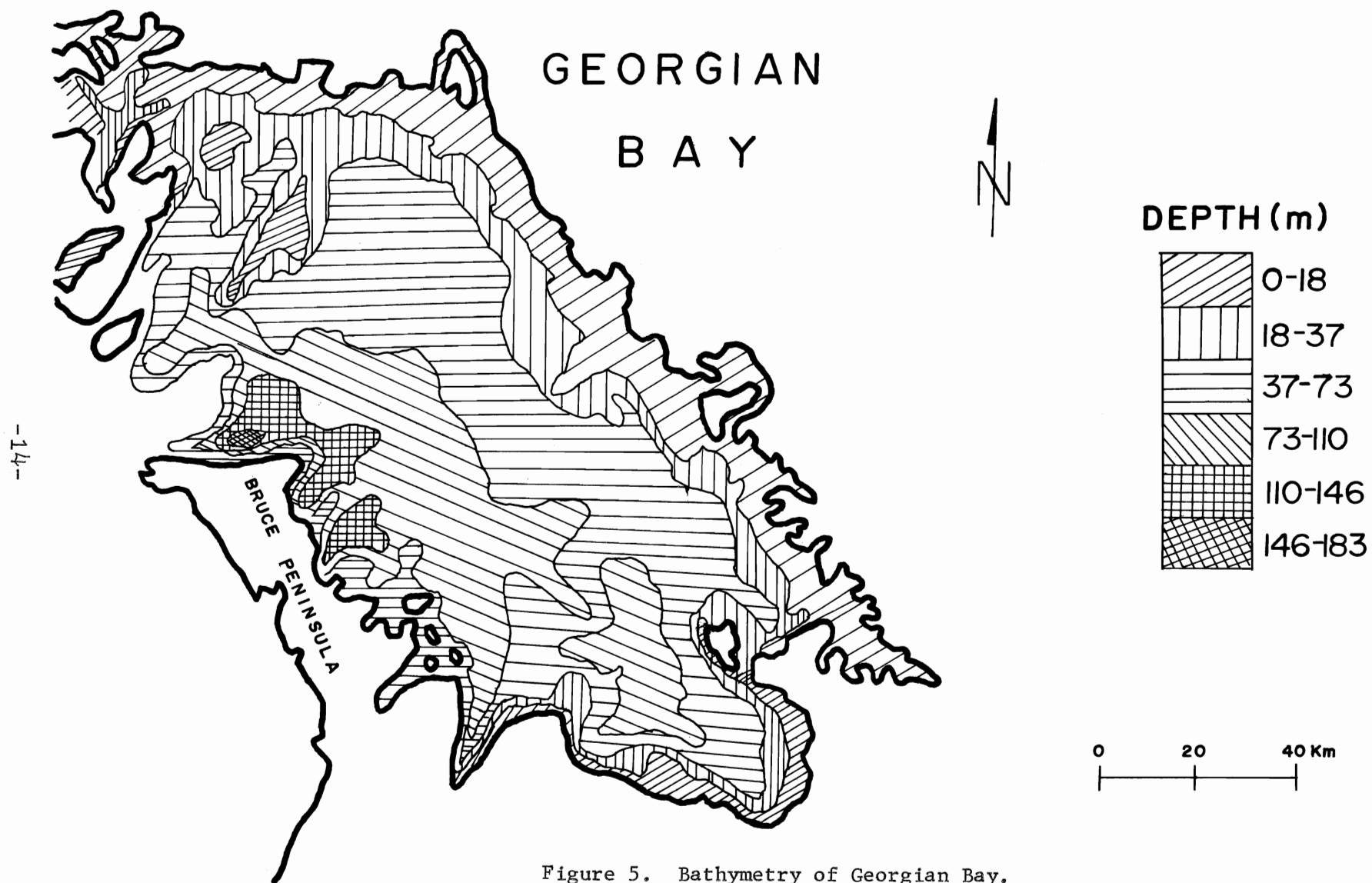


Figure 5. Bathymetry of Georgian Bay.

been described by Chapman and Putnam (1966), and the deglaciation history of this area has been reviewed by Hough (1958, 1963, 1966) and Prest (1970). The following summary of deglaciation, covering the last 13,000 years, is based on these sources and the report by Sly and Lewis (1972) and Sly and Thomas (1974).

#### Quaternary lake stages in Georgian Bay and the Lake Huron Basin

During the retreat of Port Huron ice in the Georgian Bay basin, a complex series of postglacial lakes superceded on another. After the Lake Grassmere stage, about 13,000 years B.P. (Sly and Lewis, 1972; Harrison, 1972), the Chicago outlet was cut down gradually and Hough (1958) wrote:

"When the Chicago outlet was cut down to bedrock, it established the Toleston-Algonquin level (184m) in the basin. Water surface in the Huron Basin fell to the same level because of free drainage to the Michigan Basin, cut the Port Huron outlet in till only deep enough to bring water level in the Erie Basin down to 184m. The sill could not be cut deeper at that time because lake level was determined by the Chicago outlet sill."

When the ice retreated farther, early Lake Algonquin occupied the southern part of the Huron Basin, Georgian Bay and the Lake Simcoe lowland and about 12,500 years ago, the Grand River outlet was abandoned and the glacial lake waters (Lake Algonquin) discharged through the Kirkfield-Fenelon Falls and Trent Valley river system into Lake Iroquois situated in the Lake Ontario Basin (Prest, 1970).

A subsequent readvance of ice was postulated by Deane (1950) about 12,200 years ago. This ice presumably readvanced into

the Lake Simcoe basin, following a retreat and halt to form the Lake Simcoe moraine, blocked the Kirkfield-Fenelon Falls outlet and again diverted the water of Lake Algonquin to the south through the Port Huron and Chicago outlets.

Harrison (1972) suggested that continuing ice retreat could have uncovered outlets progressively farther north, and the strandline of Lake Algonquin might be time transgressive although water level remained at about 184m. After reopening of the Kirkfield outlet about 12,000 years ago (according to Prest, 1970), this strandline in the Huron Basin extended northward into Georgian Bay and eastward around Lake Simcoe area with a gradient of 0.5-0.7m/Km along N21° E. Karrow et al. (1975) postulated that the Lake Algonquin stage probably existed between 11,500 years to 11,200 years B.P., but the basal gyttja dated in Boulter Lake (near North Bay), north of the Sobie-Guilmette outlet (of Lake Payette) indicated that the Main Algonquin to Cedar Point Lake stages existed prior to 12,000 years ago (Harrison, 1972).

After the Main Algonquin stage, the lake level was lowered to form the Wyebridge (165m), Penetang (155m), Cedar Point (150m), Payette (142m) and Korah (119m) stages. During this period, the basins of Harts Lake and Shepherd Lake were isolated and local sedimentation became dominant.

About 10,600 years ago, as the Post Algonquin Lakes discharged through the Mattawa River Valley, the lake level

in Georgian Bay dropped about 58m. At this time, the North Bay outlet carried all the discharge from the Huron, Michigan and Superior Basins. Differential uplift, caused by isostatic rebound, gradually raised the elevation of the North Bay outlet to cause the water levels in these basins to coincide (Hough,1958) and form the Nipissing Great Lakes I (three outlets). During this stage, the rise of the lake level was slow, and more glacial water was forced to flow through the Port Huron and Chicago outlets because uplift in the North Bay area was much faster than in the south. About 4,700 years ago (Sly and Lewis,1972), the North Bay outlet was raised higher than the southern outlets and discharge to the northeast ceased, and the Nipissing Great Lakes II (two outlets) developed subsequently. The oldest organic matter from the Nipissing beach has been dated at  $5,770 \pm 130$  to  $6,300 \pm 150$  years B.P. (Prest,1970).

Prior to the closing of the North Bay outlet the Port Huron outlet was lowered more than the Chicago outlet because the sill for the latter was composed of bedrock. Lake Algoma was initiated about 4,000 years ago, at an elevation of 182m a.s.l. for this reason. While differential uplift of the land in the north continued and downcutting of the Port Huron outlet also continued until the present elevation (117m) was reached (Hough,1958). Georgian Bay was initiated at this point.

### Characteristics of physiography and glacial deposits

The Georgian Bay basin is surrounded by rock upland in the east, clay plains in the south and limestone plains and the Niagara Escarpment in the west (Putnam,1952). By and large the rock knob uplands and the limestone plains are covered discontinuously by ground and end moraines, composed of stony tills, and by various glaciofluvial deposits. The depressions and lowlands are partly filled with stratified glaciolacustrine clays, silts and sands. Most bedrock was streamlined, grooved, striated and polished by the glacial moving over it. According to these abrasional features and a few drumlin-like forms found along Highway 660 in the vicinity of Harts Lake, the ice-flow direction was possibly north to south, or northeast to southwest. Wetlands and marshes exist in areas of modified drainage, particularly within the rock knob uplands of the Canadian Shield.

Glacial till, stratified beach sands and gravel, minor local ice contact deposits, stratified glaciolacustrine clays and alluvial deposits constitute the major types of surficial deposits found on the bedrock within the study areas.

The discontinuous silty till on the Bruce Peninsula was mainly derived from Precambrian rocks with some local limestone (Chapman and Putnam,1966). End moraines are almost non-existent within the Peninsula, a few occur in the Wiarton area, including the area surrounding Shepherd Lake. They are

better developed and more continuous between Collingwood and Owen Sound.

Drumlins are sparse in the vicinity of Wiarton and Shepherd Lake but they are somewhat more common near Owen Sound and indicate a southwesterly flow of the ice. The discontinuous ground moraine which covers the Guelph dolomite surrounding Shepherd Lake is thin locally and rich in dolomite and limestone clasts. The direction of ice-flow as indicated by striae and grooves on the outcrops was to the southwest.

Beach and dune deposits occur locally on the Bruce Peninsula. The beach sands of the Lake Nipissing shoreline are particularly well developed west of Wiarton.

Beach sand and gravel and some alluvial deposits have been found locally in the vicinity of Harts Lake. These overlies thin discontinuous stony ground moraine locally or they are found lying directly on the glaciated bedrock. The till and the gravel have the same general lithological composition as the local bedrock from which the clasts were derived. Some stratified glaciolacustrine clay deposits may also be found in the rock depressions near Harts Lake.

## Soil Formation, Soil Types and its Relation to Glacial Deposits

Soils in the study areas have developed during postglacial time on deposits related to the Wisconsin glaciation, and on younger deposits such as alluvial sediments. The surficial deposits in this area, in addition to vegetation and climate, have influenced the development of the different soil types.

When the Wisconsin ice advanced, it eroded most of the pre-existing unconsolidated Pleistocene sediments and blanketed the surface with glacial till and other surficial deposits ranging in size from fine clays to large boulders. Most of these deposits were derived from fresh bedrock outcrops and their texture was related to the petrographic characteristics of the rock types (Prest, 1961). During the general recession of Wisconsin ice, the ice readvanced short distances several times (Dreimanis, 1961), and the ice sheet reworked some of the pre-existing unconsolidated deposits, producing a fine-grained till matrix, especially when glacial lake sediments (in silt and clay size) were incorporated in it. Lee et al. (1957) suggested that the till consisted mainly of reworked reddish brown silts and clays, and sometimes with a small admixture of gravel derived from old till and/or the bedrock. After the area became ice-free, the processes of weathering initiated the development of the Holocene soil profiles.

The podzolic soils in Harts Lake area are commonly



sandy and gravelly because the surrounding bedrock contains minerals that are relatively resistant to abrasion and weathering. The local surficial deposits (thin till) contain about 71% coarse grained sand and granules and about 7% clay (Dreimanis, 1961). Relatively few calcareous grains (1-3%) occur in the Harts Lake till primarily because the source (Grenville marble) is highly localized and scarce. Grains of quartz and feldspar are the most abundant mineral fragments found in this till.

In the Shepherd Lake area, where the glaciers overrode Paleozoic limestone, shale, dolomite or pre-existing glacial deposits, the brunisolic soils are clayey or silty in texture and they have a high carbonate content. Dreimanis (1961) showed that Precambrian constituents comprise 15% of Southern Ontario soils. In the pebble and granule size Precambrian component ranges from 5% to 20% of the clasts. Richards (1961) noted that more than five hundred soil types have been identified and mapped in Southern Ontario. Soil taxonomy is dependent on climate, vegetation, the composition of the bedrock, topography and the duration of the development. Because the soil development is a chemically, physically and biologically complex system, the constituents are constantly undergoing change. On the basis of profile characteristics, soils are grouped in Orders, Suborders, Great Soil Groups and Subgroups (Table 1).

Table 1. A Classification of Soils: Orders, Suborders,  
Great Soil Groups and Subgroups (Modified from  
Richards, 1961; and Buckman and Brady, 1969)

Orders	Suborders	Great Soil Group	Subgroups
Brunisolic Intrazonal Soils	Calcimorphic Soils	Brown Forest	1a. Orthic Brown Forest
			1b. Degraded Brown Forest
			1c. Gleyed Brown Forest
		Grey Brown Podzolic	2a. Orthic Grey Brown Podzolic
			2b. Brunisolic Grey Brown Podzolic
			2c. Gleyed Grey Wooded
Podzolic Zonal Soils	Light-Colored Podzolic Soils of Timbered Regions	Grey Wooded	3a. Gleyed Grey Wooded
		Podzol	4a. Orthic Podzol
			4b. Bisequa Podzol
			4c. Gleyed Podzol

The soils of the Shepherd Lake area can be classified as " Brunisolic Soils " of the orthic brown forest and the gleyed brown forest subgroups. They have developed under deciduous forest on calcareous deposits (limestone, dolomite or till) with good to deficient drainage. The soils are very shallow, with much bare dolomite exposed. The A<sub>1</sub> horizon is about 10-13cm thick with a dark organic surface. The B horizon is approximately 15-25cm thick and is underlain by strongly calcareous C horizon, at a depth of roughly 38-46cm.

The pH value of soils on the Bruce Peninsula is generally 7 or slightly higher than 7, and there is no marked eluvial or illuvial horizon. Chapman and Putnam (1966) stated that Brunisolic soils cover about 1,000 Km<sup>2</sup> on the Bruce Peninsula, including the Shepherd Lake area. The Guelph Formation, with its monoclinial structure exhibiting a southwesterly dip and the thin discontinuous calcareous till overlying the dolomite, are responsible for the development of the Brunisolic soils. Southwestward in the Owen Sound district, the drainage becomes imperfect due to the presence of hydrated iron, probably originating from the traces of pyrite in the Manitoulin Formation. This area belongs in the gleyed brown forest soils, in which the A<sub>1</sub> horizon is thicker than the A<sub>1</sub> horizon of the orthic brown forest soils. The distribution of these two soil types is strongly related to the underlying bedrock. Liberty and Bolton (1971) stated that the abrupt change in lithology between the Lockport dolomite (overlain by the orthic brown

forest soils) and underlying Cabot Head shale (characterized by the gleyed brown forest soils) was due to a sedimentary break between these two formations. Due to these lithological and sedimentary characteristics and the more imperfect drainage on the Cabot Head Formation, orthic soils can develop better on the Lockport Formation than gleyed soils on the Cabot Head Formation.

The soils in the Harts Lake area are of the podzol orthic type. They have humoferric podzol and dystic brunisol groups developed in well-drained areas, and with organic matter (peat) cover in poorly-drained areas (Rowe,1972). All of them have a strongly weathered and leached grey A<sub>2</sub> horizon, lower pH value and consequently low base saturation (Richards,1961). Commonly, the A<sub>0</sub> horizon is about 2.5cm thick; the A<sub>2</sub> horizon is grey in colour and about 5-10cm thick. It overlies B horizon which ranges from 15cm to 50cm in thickness. The main accumulation products in the B horizon are organic matter and/or hydrated iron.

#### Climate

Generally, the summer in the Georgian Bay Region is warm with frequent periods of hot, humid tropical air from the Gulf of Mexico, and the Lake Simcoe area can reach a maximum high temperature about 40°C. During the winter season, temperatures can remain below freezing for about 4-6 months because cold

arctic air dominates the area. The resulting extremely low temperatures can range from  $-45.5^{\circ}\text{C}$  to  $-32.2^{\circ}\text{C}$  on the east shore of Georgian Bay (Putnam,1952;Phillips and McCulloch,1972).

The mean annual temperature of Georgian Bay area ranges from  $5^{\circ}\text{C}$  to  $7^{\circ}\text{C}$ , with mean daily temperature ranging from  $-12^{\circ}\text{C}$  to  $-6^{\circ}\text{C}$  in January, and  $18^{\circ}\text{C}$ - $10^{\circ}\text{C}$  in July (Brown et al,1974). Some large variations in temperature may occur over relatively small distances because of topography, water and vegetation cover. Winter isotherms follow closely the outline of the Great Lakes shores. On the Canadian Shield, the winter temperature increases from  $-13^{\circ}\text{C}$  in the Lake Nipissing area to  $-8^{\circ}\text{C}$  in the Lake Simcoe area, but west of Georgian Bay at the same latitude, the temperature only ranges from  $-7^{\circ}\text{C}$  to  $-5^{\circ}\text{C}$ . The difference is caused by topography, the moderating influence of the Great Lakes (Lakes Huron,Michigan and Georgian Bay) and the prevailing wind (from west and southwest).

The mean annual precipitation ranges from 81cm in the Nottawasaga Bay to 102cm in the Muskoka region, controlled by the slope and the elevation of the land, location relative to the lakes and prevailing wind direction. The Muskoka region receives the heaviest precipitation in the whole study areas, caused by the westward slopes of the highland of the Canadian Shield. The greater part of summer rainfall results from showers and thundershowers of short duration and overcast or rainy days are comparatively rare during the months of June,

July and August (Brown et al.,1974). In the winter, the distribution of snowfall is similar to that of total precipitation, relating to the lake effect. The mean annual snowfall is over 279cm in Georgian Bay with the maximum (over 350cm) in the Nottawasaga Bay and winter precipitation often exceeds that of summer (Meterological Branch,1962).

In addition to the pricipitation, the frost-free period is also lake affected because the lake diminishes the difference between day and night temperatures. The pattern of average length of frost-free period is closely similar to the pattern of the isotherms of July mean temperatures. It is the longest in Lake Simcoe area (about 140 days) and decreases northwesterly to 84 days. This pattern is also concordant to the isopleths of extreme high temperature (Putnam,1952).

The prevailing winds are from the west, south and southwest directions for more than fifty percent of the year. They are strongest in winter and spring, and lightest in summer (Brown et al.,1974). The mean daily wind speed varies from 12 to 21Km/hr in winter and 9.5-16Km/hr in summer.

#### General Description of the Lake Bottom Sediments

Mainly, there are four kinds of lake bottom sediments in Georgian Bay;i) undifferentiated till,ii) sand,iii) glacio-lacustrine clays and iv) muds. Among them, muds occur in two distinct sedimentation zones (Thomas et al.,1972;Sly and Thomas,

1974; Kemp and Harper, 1977) (Fig. 6);

- a) Depositional basin, where fine-grained sediments are actively accumulating at the present time, majority are clay- and silt-size particles.
- b) Non-depositional zones, that are composed of bedrock, glacial till, glaciolacustrine clays and sand.

According to the Georgian Bay bathymetrical map (Canadian Hydrographic Service, 1971; Kemp and Harper, 1977), six depositional basins are recognized: Flowerpot, Cabot Head, Nottawasaga, French River, Lion's Head and Owen Sound (Fig. 7). Since these six depositional basins collectively comprise all the mud sediments, thus they are affected by bathymetry, bottom topography and bedrock.

The eastern part of Georgian Bay is characterized by undifferentiated till, bedrock, glaciolacustrine clay and minor amounts of sand. As a consequence of bedrock and these deposits, the water depth is usually less than 37m. Some of the till is surrounded by glaciolacustrine clays in the central basin, due to bottom topography, bedrock outcrop, current direction and type of deposition.

As a consequence of bathymetrical complexity, only a small area of sand was found in the south part of Nottawasaga Bay (Wasaga Beach) with water depth less than 7.3m (Sly and Thomas, 1974). The sand is transported into Georgian Bay by the Nottawasaga River today. The derivation of sand is mostly

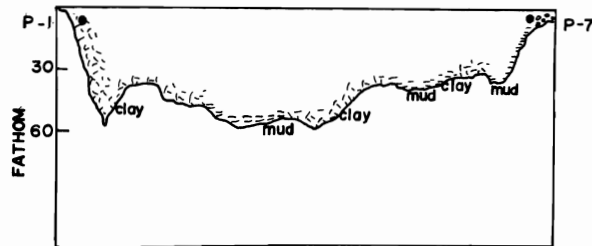
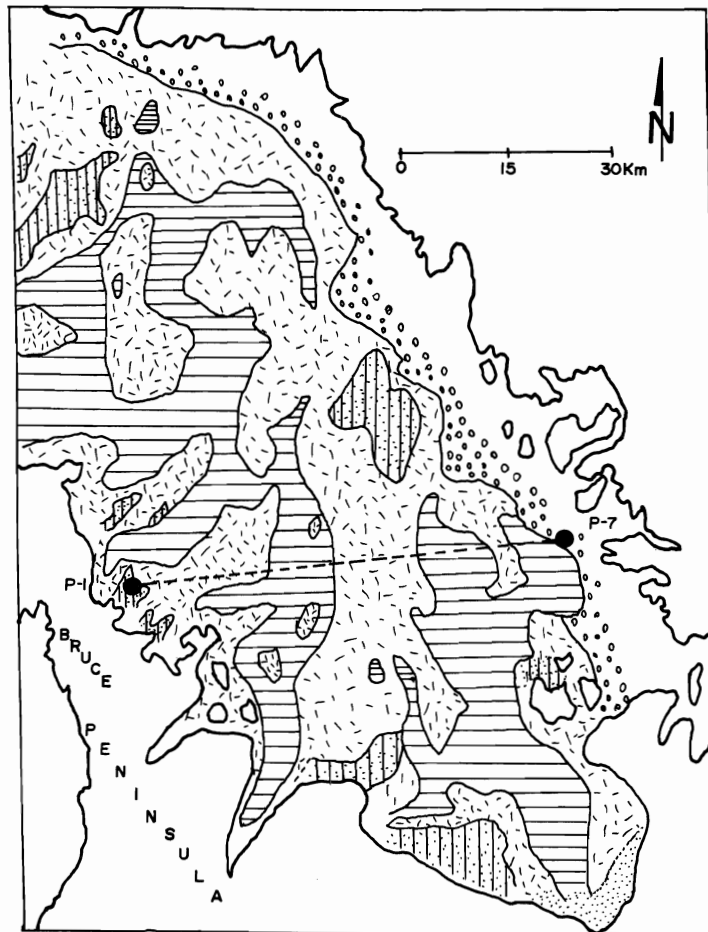


Figure 6. The distribution of Georgian Bay surface bottom sediments (After Sly and Thomas, 1974).

## LEGEND

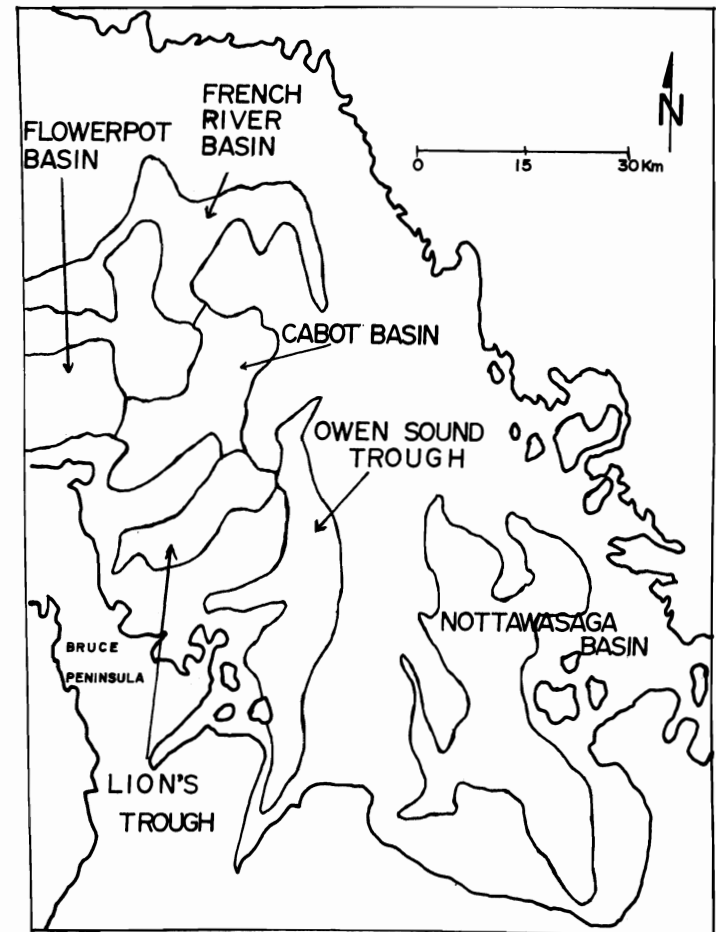
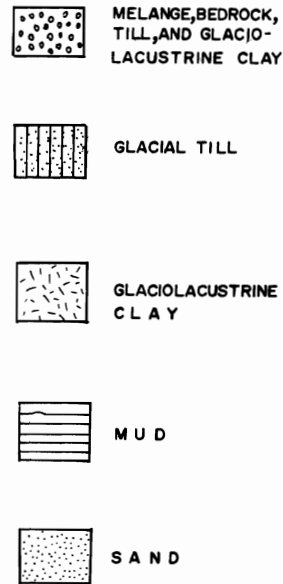


Figure 7. Six depositional basins of Georgian Bay (From Kemp and Harper, 1977).



from the mantle of glacial drift on bedrock (Hough,1958).

The unweathered surficial deposits (mainly bedrock detritus) were originally transported by glacial ice. After ice retreat, the streams and shore currents eroded these glacial deposits and the shore bluffs, and contributed sediments to the lake. Hough(1958) stated that the grain size of sand decreased with increasing distance from the source and the depth of water. The sorting of the fine-grained sand is better than the coarse-grained fraction. As the distance of transport increases, the sorting gets better and better. For the sand in Georgian Bay, the good sorting is due also to the same parental glacial drift and bedrock material. Since the depositional process is not long enough, a low degree of roundness and the immaturity is the characteristics of the sediments.

Glaciolacustrine clays are the most abundant sediments in Georgian Bay, derived from reworking of glacial till (quartz, feldspar, clay minerals and carbonates) in sand, silt and clay size fractions (Thomas et al.,1972; Kemp et al.,1974). The clays occur in the west and central part of the Bay between glacial till and offshore muds. Generally, the water depth ranges here from 73m to 146m, and distribution of the clay is predominantly affected by water depth, relief of the lake bottom and current energy. The colour of the clay varies from grey-brown to reddish brown. Sometimes, the clay contains ice-rafted pebbles or gravel (Hough,1958; Flint,1971; Dell,1972).

The fourth sediment type is mud, which is deposited in the middle of Georgian Bay by bottom currents reworking the sediments which overly the glaciolacustrine clays (Sly and Thomas, 1974). Within Georgian Bay, there are three distinct mud zones (Thomas et al., 1973):

- i) Regular basins in which mud forms a continuous cover (Flowerpot Basin, Lion's Trough and Nottawasaga Basin).
- ii) Irregular basins with irregular bottom topography. Glaciolacustrine clays outcrop on the topographic highs and mud fills in the depressions (Cabot Head Basin, French River Basin and Owen Sound Trough).
- iii) Mud covers less than 50% of the lake bottom (On the east side of Manitoulin Island, the river mouth of Panache drainage).

The mud colour varies from buffish grey to dark brown and is influenced by geological and limnological factors. Krumbein and Sloss (1963) proposed that the component material, the finer grain matrix (cement), the coating of the grains and the degree of fineness can control the colour variance.

During a study of the palynology of the Georgian Bay bottom sediments by Anderson and Terasmae (1966), it was found that in the western part, the mud is grey and of silt clay size, but in the southeastern part (Nottawasaga Bay), the mud is brown to reddish brown, although the size is almost the same. Probably, the colour variations were due to the factors mentioned in the previous paragraph.

The distribution, properties and kinds of the sediments are closely related to the history of the Great Lakes. Three sources of the sediments can be postulated for Georgian Bay as well as for Harts Lake and Shepherd Lake. The most important one is from glacial drift, the others are related either to erosion of the shore bluffs or the transportation of suspended sediments (as the weathered product of bedrock) by rivers.

Both Harts Lake and Shepherd Lake have the same physical features- small surface area, shallow depth, poor drainage and geological origin (enclosed bedrock depressions in glaciated area). The bottom surface sediment of Harts Lake is predominantly composed of organic matter with abundant plant detritus and mud (mud:organic matter=1:4). The colour varies from dark grey to brownish yellow and is of silty clay size. Shepherd Lake occupies an enclosed basin and the sediment is organic matter and mud. The inorganic content by volume is about 5-10% in the gyttja that is underlain by inorganic glacial deposits.

## SEDIMENT SURVEY AND LABORATORY METHODOLOGY

### Sampling

Sediment samples were collected in Georgian Bay from the research vessel CSS Limnos during the period from September through October 1973 by the scientists of CCIW. In total 122 surface samples, 10 piston cores, 6 gravity cores and 2 Benthos cores were obtained following the methods described by Kemp and Lewis (1968) and Kemp (1969) (See APPENDIX I) (Fig.1). Among these samples, 109 surface sediment samples were studied for palynology by McAtee (1977) and cores P-1 and P-7 were chosen for physical, chemical and sedimentological analyses in this study.

Sediment samples from Shepherd Lake and Harts Lake were collected in June and July, 1977. The equipment and methods for the sampling of small lake sediments have been described by Mott (1966) and the same procedures were used here. The sampling methods have also been described in APPENDIX I. Four surface sediment samples, one "Brown core" (See APPENDIX I) and one piston core were collected from Shepherd Lake and seven surface sediment samples, one Brown core and one "Livingstone" piston core (See APPENDIX I) were obtained from Harts Lake (See Fig.16 and Fig.17).

P-1 piston core point was located at latitude  $44^{\circ}59'59''$  North and longitude  $81^{\circ}08'10''$  West near Lion's Head, Bruce

Peninsula (water depth about 80m, and the core length is 15.2m); P-7 was positioned at latitude  $45^{\circ}06'28''$  North and longitude  $80^{\circ}11'50''$  West, adjacent to the mouth of the Moon River (water depth about 58.5m with a core length 18.3m). Both water depths were determined by wire line and a Kelvin Hughes MS26B echo sounder.

The recovery length of P-1 core was 10.25m out of 15.2m of sediment penetrated, with a core diameter of 6.6cm. The actual recovered length was measured section by section, although some short sections might have been missed. P-7 core had a better recovery length (about 17.36m out of 18.24m). Two reasons are proposed for this difference in recovered core lengths and penetration. One was due to possibly the imperfect storage conditions in the CCIW cold room where some mix-up of cores and dewatering might have occurred over a five-year period. The other reason is related to sediment properties and coring techniques (compaction during coring might happen). Commonly, the length of a sediment core recovered is not equal to the depth interval cored (Yokoyama et al., 1975).

In Shepherd Lake a total thickness of 9.5m of sediment was penetrated by coring, and 8.94m of sediment was recovered. The recovery coefficients varied from 0.85 to 1.00, depending on the amount of the organic matter to the inorganic deposits. In Harts Lake the sediment was more silty and a total thickness of 6m was penetrated, of which 5.3m was recovered. The recovery coefficients ranged from 0.73 to 0.90.

## Subsampling

All the sediment cores were stored in a controlled environment room. The room temperature was maintained at about 4°C and 100% humidity to prevent bacterial growth, chemical change and drying of the sediment (Dzwilewski and Richards, 1974). These precautions are specially important for geochemical analyses, as well as for the palynological studies.

The sediment cores collected with the Livingstone sampler were extruded onto Saran Wrap in the laboratory by simply pushing the sediment out with an extruding rod. For Shepherd Lake (S-1) cores, the procedure was easy because the sediment was composed of soft gyttja. Harts Lake (H-1) core sediment, however, is composed of grey, fine inorganic mud and the extruding was much more difficult. The compaction during extrusion of H-1 cores was greater than S-1 cores, due to low water content, low grain-packing index and friction between core tube wall and the sediment. All the extruded cores were rewrapped with Aluminum Foil and stored in the cold room before logging. The sediment cores P-1 and P-7 had already been extruded at CCIW and had been stored in a cold room. During the extrusion, some surface smear of the sediment core is possible. Since the amount of smear is very small when compared with the total volume of the sediment core, and because the smear was carefully removed, this possible source of contamination could be neglected.

For the purpose of stratigraphic description and sediment subsampling, the cores were split carefully in half lengthwise with a spatula. One half of the cores was used for physical analysis and grain-size distribution analysis, the other half was used for chemical analysis only.

Extrusion and logging were done simultaneously for the Brown core because of the loose consistency of sediment. The tubes were kept vertically below freezing point for 12 hours. After the sediment was frozen, it could be extruded very easily in the laboratory because its contact to the core tube wall was watery. H-1 core was cut with a spatula into subsamples 3-5cm in length from 20,40,60,80cm depths. A total of 26 samples for physical analysis and 17 samples for chemical analysis were collected from the Harts Lake core between depths of 80-530cm.

Shepherd Lake core was subsampled at 20,40,60,80,100 and 120cm depths, using the same method as for Harts Lake, and an additional 44 samples for physical analysis and 18 subsamples were taken at 20-40cm intervals to 880cm depth. 40 samples were obtained from core P-1 and 60 samples were taken from core P-7. Their intervals varied from 15cm to 50cm, depending on the section length and the sediment characteristics. The colour, texture, odour and sediment type of P-7, H-1 and S-1 cores have been described in APPENDIX II.

## Analytical Techniques

This study includes physical, chemical and sedimentological analyses. Among these, the measurement of water content and pH values followed the method described by Jackson (1958), and for the determination of bulk density of all cores the method described by Griffiths (1967) and McKeague (1976) were used. The method described by Hesse (1971) was utilized to measure the loss on ignition except a smaller weight was used.

For the chemical analysis by XRF spectrometer, the preparation for the determination of major oxides differed from that described by Norrish and Hutton (1969), except that the same reagent (Lithium Tetraborate) and temperature setting ( $100^{\circ}\text{C}$ - $1100^{\circ}\text{C}$ ) were used. For trace elements, preparation procedures followed those described in the XRF handbook with minor modification of sample weight, number of X-ray tablets and pressure. The Quantimet 720 TV Image Analysing Computer (Quantimet) was used for direct measurement of grain size (from sediment grains mounted on microscope slides) without the traditional pipette method because of restriction of the sample amount and characteristics of the sediments. The method of sample preparation followed that described by Perrie and Peach (1973) and Peach and Perrie (1975).

The total number of samples analyzed was: 159 samples for



physical properties, 11 samples for pH value, 100 samples for major oxides, 116 samples for trace elements and 62 samples for grain size distribution. The procedures of sample preparation have been described in detail in APPENDIX III. Some of the XRF spectrometer's parameters for chemical analysis, trace element analysis of the standrocks and the statistical tests of the standard rocks were listed in APPENDIX VI for reference.

## SEDIMENTOLOGY OF THE LAKE SEDIMENTS

### Grain Size of the Sediment and Depositional Environment

The sediments of the study areas were transported into the depositional basins by glacial processes and/or fluvial action. Glacial ice can move sediment particles of any size and weight without lateral diffusion or sorting because of the high density and the internal friction of sediment particles (Reineck and Singh, 1975). The glacial drift itself had no obvious arrangement of its component particles and the nature of the glacial sediments was controlled by five main factors (Kukal, 1971):

- 1) Character of bedrock on which the glacier moved.
- 2) Geomorphology and velocity of glacial movement.
- 3) Position of the transported material in relation to the moving glaciers.
- 4) Mode of transportation and deposition.
- 5) Subsequent reworking or redistribution by meltwater.

As the main deposition took place during the recession of the glaciers, meltwater would affect "pure" glacial drift by reworking and redistribution because water is an important factor for the origin of sedimentary characteristics. Some pebbles could be rafted by floating ice during the recession of the glaciers and Flint (1971) stated that the number of these pebbles diminished upward and decreased from their source.

These pebbles show significant orientation in the lake sediments and could be affected by factors 1),4) and 5).

Reineck and Singh (1975) also described the sediment size characteristics in a lake basin during glacial recession. The lake would receive its sediment supply during warming periods of spring and summer when ice melted and glacial streams brought a large amount of sediments to the lake basin. Gravel and coarser sand were deposited near the lake shore, and fine sand, silt and clay were transported farther out into the central part of the lake in suspension. In the cold winter, there was no sediment supplied from the adjacent landscape, and a clay layer would be deposited on a sand (or silt) layer to form a varve deposit (if there was no reworking or redistribution inside the lake basin). These deposits were rhythmically laminated, having alternating coarser and finer laminae to represent an annual cycle of deposition and they could be used as a basis of time calculation. The pebbles and laminations are common features in the core stratigraphy as described in APPENDIX II.

After the retreat of the glaciers, the most significant period of fluvial transportation was initiated probably about 11,200 years ago during the Post Lake Algonquin stage. During this period, Georgian Bay could receive glacial water from Post-Duluth Lakes via Lake Michigan and Lake Huron when drainage was through the Mattawa Valley to the St. Lawrence River system (Hough,1958;Prest,1970;Harrison,1972). This fluvial transportation could bring the sediment from its watershed when the

sediment was produced by erosion of the surficial (glacial) deposits.

With regard to sediment distribution in Georgian Bay, the coarser grains were deposited near the shore, whereas fine clastic material (very fine sand, glaciolacustrine clay and mud) in suspension was transported farther. Probably, this sediment distribution was related to the transporting energy and competence because Pettijohn (1975) proposed that the transporting energy and competence could be decreased exponentially with increasing distance. Furthermore, Thomas et al. (1973) suggested that erosional mechanisms (shoreline erosion and bottom erosion) were more significant than fluvial transportation (river input) on a lake-wide basis for the sediment distribution. Thus, almost all the sediments could be reworked and redistributed by these erosional mechanisms after their deposition.

Many sedimentologists have studied grain-size (texture) characteristics (Krumbein and Pettijohn, 1938; Gaither, 1953; Sarmiento and Kirby, 1962; Pettijohn, 1975) and their relationship to the depositional environment (Spencer, 1963; Folk, 1966; Griffiths, 1967; Koldijk, 1968; Visher, 1969; Solohub et al., 1970; Pettijohn, 1975). The sediment characteristics usually indicate that along the direction of transport, the grain size decreased as the distance from its origin increased. The balance was transported into the lake basin or sea, dependent on grain size, shape, density, roundness and sphericity.

Pettijohn (1975) stated that two physical processes were involved for the grain-size decrease-- abrasion (10%) and progressive sorting (90%, selective transportation). The progressive sorting was more important due to the physical properties of sediments. Kukal (1971) studied the different sediment shape with a similar size in a fluvial environment, and found that the suspended material would distribute regularly in the flowing water channel. The flat particles would rise higher or stay in suspension longer than spherical ones. The roundness and sphericity will increase proportionally with distance, but conversely, the sorting coefficient will decrease with the grain size. As the energy of the flow becomes less competent, sediment particles start to settle down in accordance with the "Stoke's Law".

#### Sediment Size Analysis

The Quantimet was used to measure grain size directly in numbers although it does not provide information about particle shape, composition, weight or degree of agglomeration. This size distribution is most useful in characterizing the sediment particles as a component of the sediment but yields little or misleading information regarding the behaviour of the constituent particles in the active sedimentation processes (Schubel, 1969). The sediment analyzed (less than 2mm) consisted of four major components: i) silt-size silicate particles, mainly detrital quartz and feldspar; ii) clay mineral particles; iii) siliceous

and calcareous tests of unicellular organisms and iv) amorphous living or dead organic matter. Owing to this heterogeneous nature, the same sample would yield many different number-size distributions (Swift et al., 1972). Griffiths (1967) emphasized that the size distribution in the sediments was a function of the size and shape of the grain, the orientation of the grain and packing and mineral composition of the grain. These factors reflected the hydrodynamic conditions during the deposition of the sediments. Under a high hydrodynamic condition, due to high energy, the grain size should be coarser than the grains in the low hydrodynamic condition. Thus, the grain size distribution obtained by Quantimet measurement could reflect the energy of the depositional environment.

For this study, the traditional pipette method was not used because of the small amount of the sample and the variable compositions of the sediments (Griffiths, 1967). Not only were the two methods of analysis based on different principles (One was dependent on the Stoke's Law and the other on direct measurement of the image), but also they were measured differently (the former was in weight percentage and the other was in number-size). If the chemical composition of the sediments was simple and its varied in a narrow range, the pipette method was preferred because Carver (1971) compared the measurement by Quantimet (of grain mounted on microscopic slides) to that of pipette method, and found that the direct measurement scanning across the sediment grains horizontally would indicate coarser

size than the pipette method. Although the pipette method is more popular, it still could have flat, irregular grains been categorized into a smaller size fraction because their "zigzag" settling pattern would prolong the settling time. Griffiths (1967) concluded from all the measurements by different methods that any attempt to interpret the exact meaning of the measurement in terms of absolute size was difficult and impossible.

In this study, size analysis was used for relative comparison only. The conversion of scale in phi units from diameter range into the same scale by volume or weight percentage postulated that all the grains were spherical ( $V = 4/3 * \pi * r^3$ ) with identical density ( $W = Vd$ ), and the method of Griffiths (Sec. 5.5, Table 5.4) was applied. Although sand fraction is important in the analysis of sediment grain size, the sand fraction was excluded in this study because its grains were much coarser than that of silt and clay fractions (it will affect the accuracy of the conversion as mentioned above) and only a small amount was found (less than 1.5%) inside the lake basin (Sly and Thomas, 1974; Kemp and Harper, 1977). The counting range for the Quantimet was set up to 64 microns (in diameter) with six different size fractions (See APPENDIX III).

#### Comparison of Sediment Characteristics

The Brown core from Harts Lake and the Brown core and the piston core from Shepherd Lake were not used, due to their high

organic content and high water content. Although organic matter represents a small percentage of the total sediment by weight, it can constitute a significant percentage by volume.

Table 2 shows grain sizes, their medians and sorting coefficients for sediments of the Upper Great Lakes and Harts Lake. From analysis of P-1, P-7 and H-1 cores, it is evident that H-1 has the highest percentage of silt fraction among all cores, P-7 has intermediate and P-1 has the greatest percentage of clay-size sediment. Since the sediment in Harts Lake was derived from bedrock either by glacial abrasion or by fluvial processes, the high silt percentage of H-1 core is due to little sorting (because of small surface area and shallow depth) and the closeness of the lake basin to the sediment sources (the bedrock of the Canadian Shield). During the transport of sediment by the Moon River or Muskoka River, the sorting coefficient could decrease proportionally with the increasing distance of transport (if the data in Table 2 were used).

The averaged sorting coefficient for H-1 is 1.19 which is higher than in P-7 (1.09) and P-1 (1.08). Since the bathymetrical complexity in the Georgian Bay is caused by underlying bedrock topography, sediment in P-1 could be reworked or redistributed by erosional processes under different hydrodynamic conditions. Also, P-7 is closer than P-1 to the Canadian Shield on the east side of the basin from which the glacier derived the drift. The average of their median values increased from  $7.96\phi$  in the east to  $8.25\phi$  in the west.



Table 2. Sand, silt and clay contents of the Upper Great Lakes  
and Harts Lake, Canadian Shield

Lake name	Number of Sample	Sand %	Silt %	Clay %	Median ( $\phi$ )	Sorting	Authors
Lake Michigan	40	10.20	30.80	59.00	8.09	1.80	(Callender, 1969)
Lake Superior	34	7.26	34.43	58.42	8.00	1.52	( " )
Lake Huron	12	0.08	36.67	63.25	8.80	1.28	( " )
Lake Huron	7	2.83	47.17	50.00	---	---	( Kemp, 1977 )
Georgian Bay	3	1.33	41.33	57.34	---	---	( " )
Georgian Bay (P-1)	23	---	31.02	68.98	8.25	1.08	( Chen, 1978 )
Georgian Bay (P-7)	27	---	39.16	60.84	8.04	1.09	( " )
Harts Lake (H-1)	12	---	42.37	57.63	7.96	1.19	( " )

For all the Upper Great Lakes, although some small areas have highly variable sediment size distributions (Reid, 1961; Thomas et al., 1973), there is a clear trend of decreasing size from Lake Michigan, Lake Superior, and Lake Huron towards Georgian Bay. Callender (1969) stated that most of the sediment from Lakes Michigan and Superior were classified as silty clays, even if Lake Superior contained some sand and Lake Michigan contained 3-11% sand. He attributed the sand-size sediment to winnowing action in high energy wave or current regime. Somers and Josephson (1968) also studied the sand in Lake Michigan, but they interpreted the sand as the deposition from the lakeward source as a relatively recent occurrence, and not necessarily requiring current and wave activity. Hough (1958) preferred the sand deposits to be the results of east prevailing winds accompanied by rain. The reason why Lake Michigan has a higher sand fraction is probably due to the removal of the carbonate by glacial water and comparatively more resistant silicates dominate the main sediment source from glacial till. Farrand (1969) studied the median diameter of sediment grain size in Lake Superior and found that it was from 0.13mm to 0.43mm on an average with a sorting coefficient ranging from 1.16 to 1.35. He suggested that the outwash sand was deposited at the front of the ice sheet as it retreated across the lake basin. Dell (1972) proposed two origins of sand in southern and western part of Lake Michigan, and stated that the sand was derived from the glacial till either by

weathering and erosion on land of surficial (glacial) materials or by subaqueous reworking of these land-derived deposits. The variation of each size fraction was also controlled by sampling site, water depth, core length, drainage pattern nearby and adjacent bedrock. In fact, there was no doubt that the same till-derived sediment could have different size fraction if different factors were involved.

After deglaciation, when the North Bay and Port Huron outlets were open, the suspended material from the Lake Superior watershed was possibly transported by southeasterly surface currents. According to Table 2, the sorting coefficients decrease from Lake Michigan (because of high sand fraction) toward Georgian Bay to indicate that in the direction of transport, the sorting becomes better by the progressive sorting and abrasion among the individual particles, between the sediment and the channel bed of flowing and its environs.

#### Stratigraphic Comparison

Owing to the individual characteristics of sediment stratigraphy of each core, Figure 8 shows significant variations in sediment size distribution (the data of silt and clay percentage are listed in APPENDIX IV). There is no overlap of the clay content graphs of H-1 and P-7 or H-1 and P-1. This suggested that the transportational and depositional environments could have a close relationship to the grain size distribution.

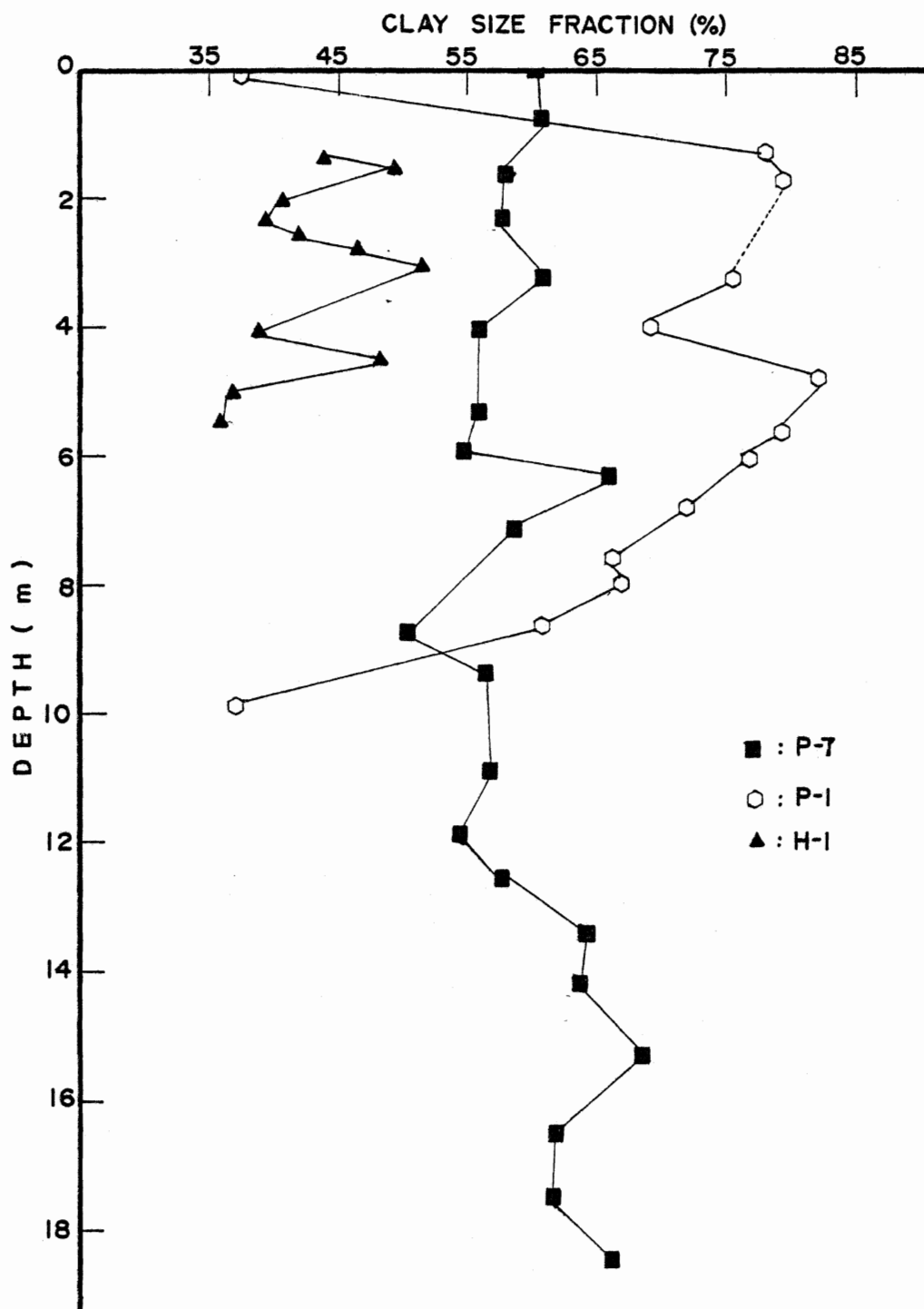


Figure 8. Stratigraphic variations of clay percentage (%) of cores P-1, P-7 and H-1 versus depth(m).

Because of the origin of the sediments, water depth at sampling site, underlying bedrock and bathymetrical complexity, Georgian Bay (P-1 and P-7) have an intermixed pattern and H-1 has a higher silt content. Reid (1961) thought that the "zigzag" trend was caused by the combined effect of the proximity of coring sites to inlet streams, relations to currents and winds, climate and the composition of the source material. He also suggested that the degree of fluctuation was more or less affected by precipitation and its seasonal distribution in the watershed. In this study, the "zigzag" pattern was also affected by the result of analysis.

On a lake-wide basis, the sediment having similar changes at the same time horizon could probably be correlated at major boundaries if more data were available. The grain size near the water-sediment interface seemed to be larger than towards the bottom of the core. Callender (1969) studied Lake Michigan sediments and concluded that the amounts of sediments in sand-size near the surface bottom were about five times more abundant than that at depth, and were proportional to their quartz content. Sirmiento and Kirby (1962) also obtained the same results based on their data from Lake Superior. In the same basin, Reid (1961) attributed this variation to the distance from shore and water depth at the sampling site.

According to Figure 8 , P-7 core has two sections of size distributions with the boundary at 1220-1283cm depth. Each size

distribution fluctuated within a certain range. We could assume that at this depth, probably, there has been a major sedimentary break. Stratigraphically, the sediments at this depth are dark yellow (5Y6/4), non-laminated and non-calcareous. For the overlain and underlain sediments, we could find some varved clay (lamination). More chemical data were needed to support this evidence.

P-1 core has the highest silt size percentage at the bottom and the top of the core. It seems that the grain size increased with decreasing depth from the bottom of the core to about 580cm depth and then decreased afterwards. Probably, it also has a major sedimentary break at this depth. The dashed line in the graph is the section missed and the actual depth is not clearly known. H-1 core has a high degree of fluctuation and is probably because it has high sensitivity to the surrounding environments as the controlling factors (currents, winds, precipitation, ...etc.) changed.

The mean, median and standard deviation (sorting coefficient) are listed in Table 3 to clearly express the size variation. P-1 core has a size range that varies from  $7.49\phi$  to  $8.76\phi$ , P-7 core has its range from  $7.82\phi$  to  $8.48\phi$ , and H-1 core has a smallest size range within  $7.84\phi$ - $8.27\phi$  (the phi scale defined by Wentworth was used). Because the results from the Quantimet analysis were adequate to characterize quartile measurement as well as the mean and the standard deviation (Folk, 1966),

Table 3. The values of mean, median, and standard deviation (sorting coefficient) of cores P-1, P-7 and H-1.

Sample Number	P-1			Sample Number	P-7			Sample Number	H-1		
# 1	7.49	7.2	1.28	# 1	8.16	8.0	1.12	#130	8.04	8.0	1.23
# 4	8.44	8.2	0.91	# 3	8.16	7.9	1.11	#150	7.84	7.7	1.33
# 7	8.51	8.4	0.90	# 5	8.05	7.9	1.23	#200	8.12	8.0	1.16
# 9	8.66	8.5	0.84	# 7	8.05	7.9	1.21	#230	8.22	8.2	1.11
#11	8.55	8.2	0.90	# 9	8.21	8.2	1.03	#250	8.09	8.0	1.27
#13	8.39	8.3	0.99	#11	8.06	8.0	1.15	#270	7.94	7.9	1.32
#16	8.89	8.9	0.86	#13	8.01	7.9	1.21	#300	7.85	7.6	1.23
#18	8.62	8.5	0.88	#15	8.05	7.9	1.23	#350	8.26	8.0	1.08
#20	8.64	8.6	0.85	#18	8.05	8.0	1.20	#400	8.18	8.0	1.16
#22	8.51	8.4	0.97	#20	8.34	8.1	1.08	#450	7.96	7.8	1.29
#24	8.76	8.5	0.82	#23	8.12	8.0	1.14	#490	8.27	8.2	1.03
#26	8.47	8.4	1.00	#25	8.07	8.1	1.18	#530	8.27	8.1	1.06
#27	8.68	8.5	0.88	#29	7.82	7.7	1.02				
#28	8.35	8.2	1.07	#30	8.45	8.2	1.01				
#29	8.17	8.1	1.20	#32	8.04	7.9	1.03				
#30	8.33	8.2	1.03	#34	8.46	8.3	0.99				
#31	8.40	8.4	1.01	#37	8.08	7.9	1.16				
#32	8.33	8.3	1.09	#40	7.95	7.8	1.06				
#34	8.38	8.3	1.05	#42	8.10	8.0	1.11				
#35	8.18	8.1	1.10	#44	8.30	8.2	1.06				
#37	8.42	8.3	0.97	#47	8.26	8.1	1.08				
#39	8.14	8.0	1.12	#50	8.41	8.2	0.96				
#40	7.59	7.2	1.30	#51	8.24	8.1	1.05				
				#52	8.48	8.4	0.98				
				#54	8.24	8.0	0.96				
				#57	8.25	8.2	1.04				
				#60	8.30	8.1	0.94				
	8.38	8.25	1.00		8.17	8.04	1.09		8.08	7.96	1.19
	Mean	Median	S.D.		Mean	Median	S.D.		Mean	Median	S.D.

\* S.D.= Standard Deviation

Trask's sorting coefficient is listed in APPENDIX IV for comparison with this sorting coefficient by using the equation: sorting coefficient =  $\sqrt{Q_3/Q_1}$ . The trend of sorting coefficient here is the same as Trask's but generally with a higher value because Trask used a geometric expression and this study used an arithmetic calculation.

In respect to sorting coefficient, the higher values correspond to poor sorting (Folk, 1966), and it has a linear relationship to mean grain-size distribution affected by factors proposed by Pettijohn (1975). If we applied grain-size indices classified by Doeglas (1968) (See APPENDIX IV), all the samples analyzed belong to the categories of fine silt to very fine silt and clay, and were formed in a very low energy, quiet environment because of negative skewness (Folk, 1966). Due to these narrow ranges of size distribution and high clay fraction (over half the samples analyzed), the mean values are slightly higher than the median values shown in Table 3.



## PHYSICAL CHARACTERISTICS OF LAKE SEDIMENTS

### Results of Analysis

The analysis of physical characteristics of sediments has included determination of water content, bulk density and loss on ignition (L.O.I.) at two different temperatures (as described in the "Physical Analysis"). Since P-1 core had been exposed too long and the storage condition were questionable, the water content and bulk density were not determined.

Bulk density can be expressed in two different ways because it is a characteristic of sediment aggregates in its "natural" condition (Griffiths, 1967). One is the value of the total original weight to the original volume and the other is the dried weight to the original volume (Kominz et al., 1977). The former value is higher and more practical, especially we are dealing with the organic sediments in cores S-1 and the Brown core of H-1. Normally, the bulk density of sediment (as determined by Griffiths, 1967) varied from  $1.5 \text{ g/cm}^3$  to  $2.9 \text{ g/cm}^3$ . For the sediment with high organic content, the value will be much lower than this range because of low content of inorganic matter. The bulk density value can be used to trace the change in lithology of a formation and to calculate the effect of compaction of the sediment. The L.O.I. measurement in this study was different from that used by some other authors' (Gacs, 1975; Rosmann and Seibel, 1977) for the temperature

setting, and therefore their results could not be used for comparison.

As shown in Table 4, S-1 core has the highest average water content of 82.92% which is much higher than that of cores P-1 and P-7. For bulk density, the result is inversely proportional to the water content. P-7 has the highest average bulk density of  $1.76\text{g/cm}^3$  which is higher than that of H-1 ( $1.41\text{g/cm}^3$ ) and S-1 ( $1.10\text{g/cm}^3$ ).

The interstitial water could be totally driven off if the oven temperature of  $110^\circ\text{C}$  was held for 24-30 hours. After this, the samples did not contain any free water (except structural water in the structure of the sediment). Loss on ignition measured at  $450^\circ\text{C}$  would measure the loss of organic matter from the sediment (Jackson, 1958; Hesse, 1971). S-1 core has the highest average value in the sequence S-1 (52.48%) > P-7 (7.78%) > H-1 (3.9%) > P-1 (3.09%). When the temperature was increased to  $1100^\circ\text{C}$ , this sequence was changed as S-1 (64.81%) > P-1 (11.55%) > P-7 (10.00%) > H-1 (7.2%).

#### Discussion and Correlation of Average Values

The main components of the S-1 core comprised detritus of plant and animals. Webber (1976) stated that if the organic matter was decomposed to the humus stage, it should have: 1) colloidal forms in nature; 2) porous, spongy structure with a very large surface area, and 3) high content of water, swelling

Table 4. Average values of some physical properties of  
P-1, P-7, H-1 and S-1 cores

	P-1	P-7	H-1	S-1
Water content (%)	---	55.12	42.44	82.92
Bulk density (g/cm <sup>3</sup> )	---	1.76	1.41	1.10
L.O.I. (450°C)	3.09	7.78	3.9(---)	52.48
L.O.I. (1100°C)	11.55	10.00	7.2(9.67*)	64.81

\* Values included the "Brown core" samples

on wetting and shrinking on drying. If the lake environments, water depth and sediment were similar, the water content of the sediment should be more or less in the same range. S-1 core has an average water content of 82.92%, similar to an average of 80.31% in the Perch Lake (Gacs, 1975). Since most of the influent and effluent of Perch Lake is via Perch Creek to the Ottawa River and more inorganic sediment could be brought in by this fluvial process than in Shepherd Lake.

Meade (1966) studied the terrigenous sediments in lake, sea, gulf and bay areas, and concluded that as the median diameter of the sediment particles increased, the porosity should decrease (Fig. 9). As the sediment grain size of H-1 core is generally larger than that of P-1 and P-7, the water content of H-1 should be lower than that of P-1 and P-7. Furthermore, clay minerals smaller than 2 microns in P-1 and P-7 have a large specific area and strong electrostatic interparticle forces. The result of this is an open structure and the sediment porosity of P-1 and P-7 should be higher than H-1. Figure 10 shows that P-7 has higher porosity than H-1 because P-7 core has

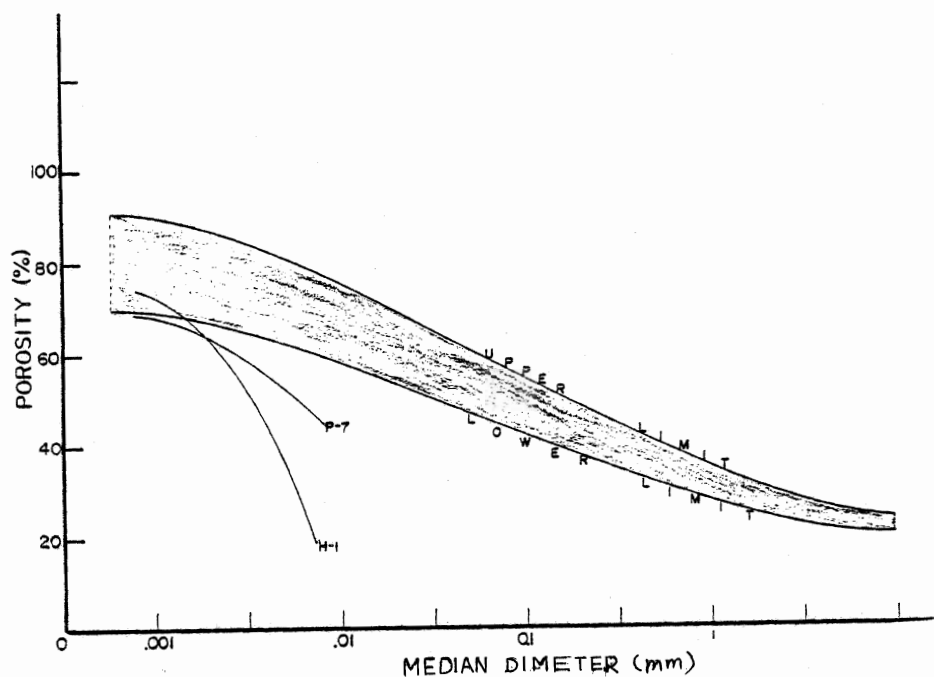


Figure 9. Relationship between porosity and median diameter of sediment particles (Modified from Meade, 1966).

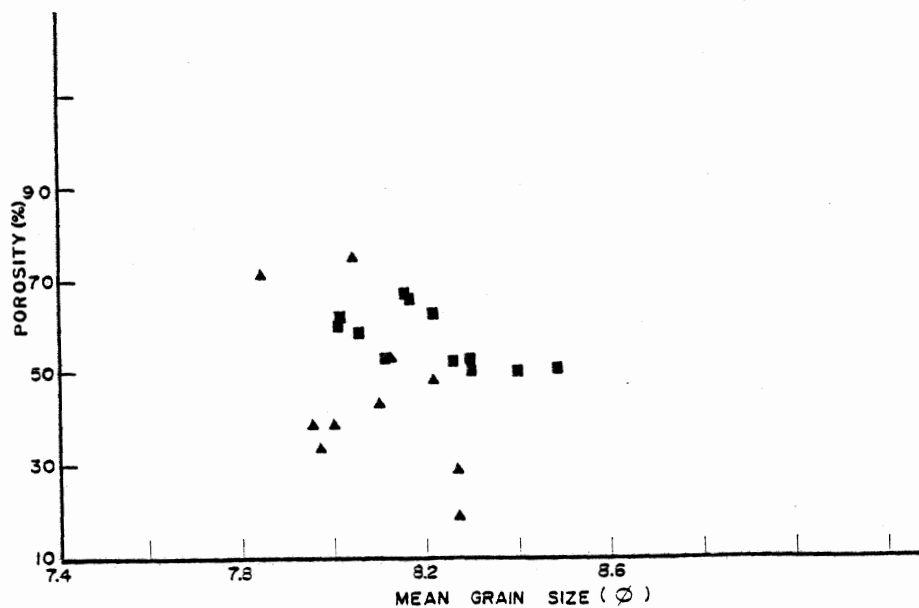


Figure 10. Relationship between porosity and mean grain size.

a smaller grain size than that of H-1 core sediment and also because P-7 has an identical sediment stratigraphy.

Berner (1971) postulated that an increase in angularity of the sediment grains would cause a slight increase in porosity, whereas good sorting would cause a large increase in porosity. Since H-1 has a poorer sorting than P-1 and P-7, it could have a lower water content if Berner's statement was applicable.

The bulk density of S-1 core is the lowest among the cores studied because of its high water content, low grain density (high organic matter content) and loose aggregate packing. The porosity is inversely proportional to the bulk density, and the water content is proportional to the porosity (Griffiths, 1967). Thus, Figure 11 shows a good correlation between bulk density and water content for H-1, P-1 and P-7 cores. The correlation coefficient for S-1 is the best ( $r=-0.907$ ), and P-7 ( $r=-0.903$ ) and H-1 ( $r=-0.892$ ) are also good. For H-1 core, the sediment contained relatively abundant organic matter and the mud was predominantly beginning at 183cm depth. Because of these two fundamental difference of the grain density, the bulk density was affected.

When P-7 and H-1 were compared, it seemed that the sediment in larger, deeper basin (Georgian Bay) had a higher bulk density. Probably, it is related to water depth, organic matter content, sediment type and compaction by overlying sediments. The average organic matter content for P-7 is higher

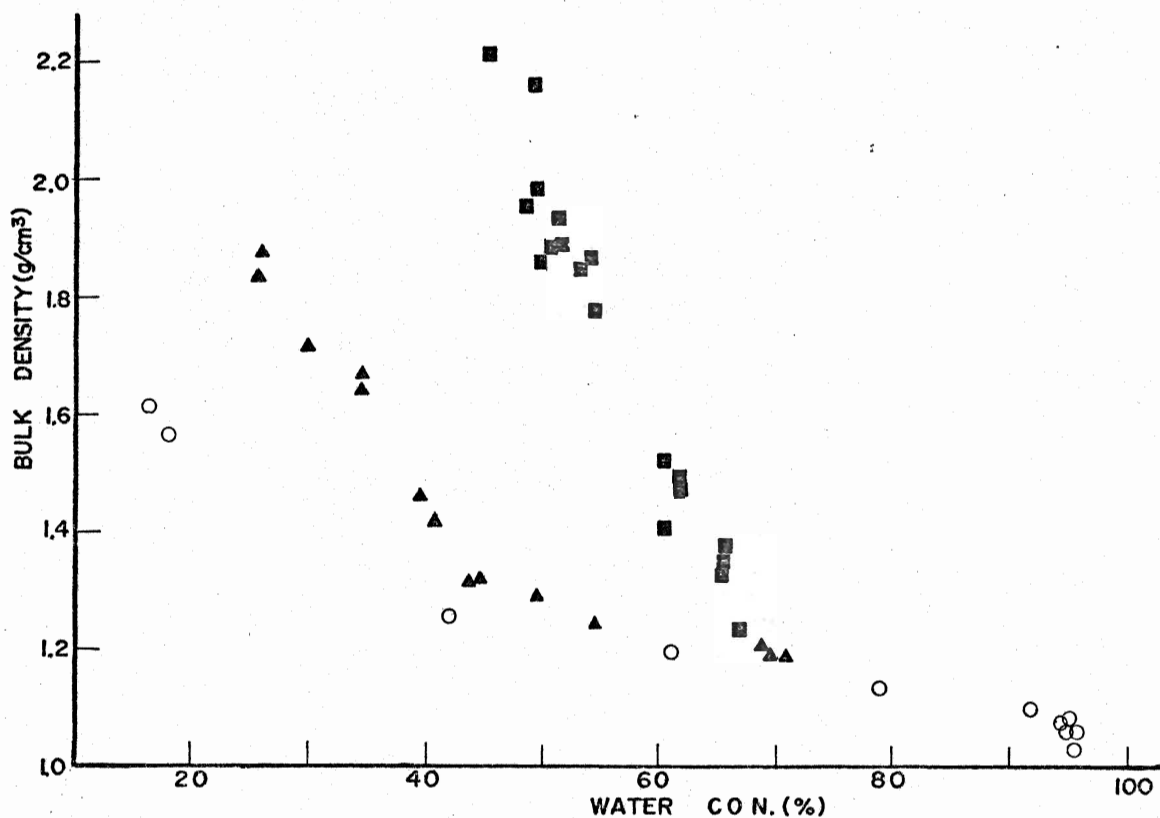


Figure 11. Relation between water content (% , as an equivalent of porosity) and bulk density ( $\text{g}/\text{cm}^3$ ) of H-1, P-7 and S-1 cores.

than that of H-1 although H-1 has a very high organic content (21.7%) near the surface in the Brown core.

As mentioned previously, P-7 core having higher water content is because it has smaller grain size than H-1 core. How could P-7 have such higher bulk density than H-1? Unless more iron (specific density  $d=7.86\text{g}/\text{cm}^3$ ) or aluminum ( $d=2.7\text{g}/\text{cm}^3$ ) than silica ( $d=2.3\text{g}/\text{cm}^3$ ) contents existed in the sediment of P-7 core, there is really no other reason could explain this phenomenon. From next chapter, the chemical data could probably be used to prove this speculation.

Griffiths (1967) suggested that interdependence between sediment type, bulk density and water content of the samples could reflect the interactions between the sediments and the environmental (depositional) conditions. Thus, the bulk density of P-10 core measured by McAtee (1977, personal comm.) was similar to that of P-7 core and a range from  $1.2\text{g/cm}^3$  to  $2.0\text{g/cm}^3$  was recorded.

For the L.O.I. at  $450^\circ\text{C}$ , S-1 has the highest value because of its highest organic content. P-1 core has a lower value of L.O.I. at  $450^\circ\text{C}$  than P-7 core. Probably, P-7 could have more organic matter derived from the Canadian Shield than P-1 from the Bruce Peninsula because of the differences in watershed characteristics and drainage. The comparison between P-7 and H-1, is based on differences in sediment transportation, different specific density of sediment grains and the lake's catchment area. The organic matter input to Georgian Bay from its watershed should be much higher than that to Harts Lake from its smaller watershed by the characteristics of watershed, fluvial processes and depositional environment.

As the temperature was raised to  $1100^\circ\text{C}$ , all the structural water and the carbon dioxide from calcareous material was expelled. The difference in the L.O.I. at  $450^\circ\text{C}$  and  $1100^\circ\text{C}$  is much greater in P-1 and S-1 than in P-7 and H-1. P-1 core has a difference of 7.23-11.19% with an average of 8.46%, and S-1 has a difference of 3.86-13.24% with an average of 11.97%.

P-7 and H-1 have a L.O.I. difference about 1.29-2.93% (with an average 2.22%) and 1.1-4.21% (with an average 3.3%), respectively. Since the difference of the L.O.I. measurements at 450°C and 1100°C is higher in P-1 and S-1 than in P-7 and H-1, and the difference is an equivalent of the carbonate content. Thus, the Paleozoic carbonate strata probably contribute some carbonate material to the lake sediments as a result of weathering and erosion.

### Stratigraphic Correlation

Figure 12 and Figure 13 show the results of analysis of the water content (110°C), the bulk density, L.O.I. at 450°C and L.O.I. at 1100°C of the lake sediments versus the depth. The water content decreases with the increasing depth. This suggests that compaction is closely related to the deposition of overlying sediments. As the original water content (porosity) of the sediment at the time of deposition was controlled by the composition and the grain size, some variations of porosity would occur if the modes of packing or sorting of different minerals were changed (Berner, 1971).

Meade (1966) stated that an order-of-magnitude difference in median diameter of particles between 1.00mm and 0.975 microns could cause a significant amount of variation in porosity at the same depth, because during the stage of compaction, particles' size is as important a factor as the overburden load. For example, at 10m depth, the clay (2 $\mu$ ) could have a 80% porosity



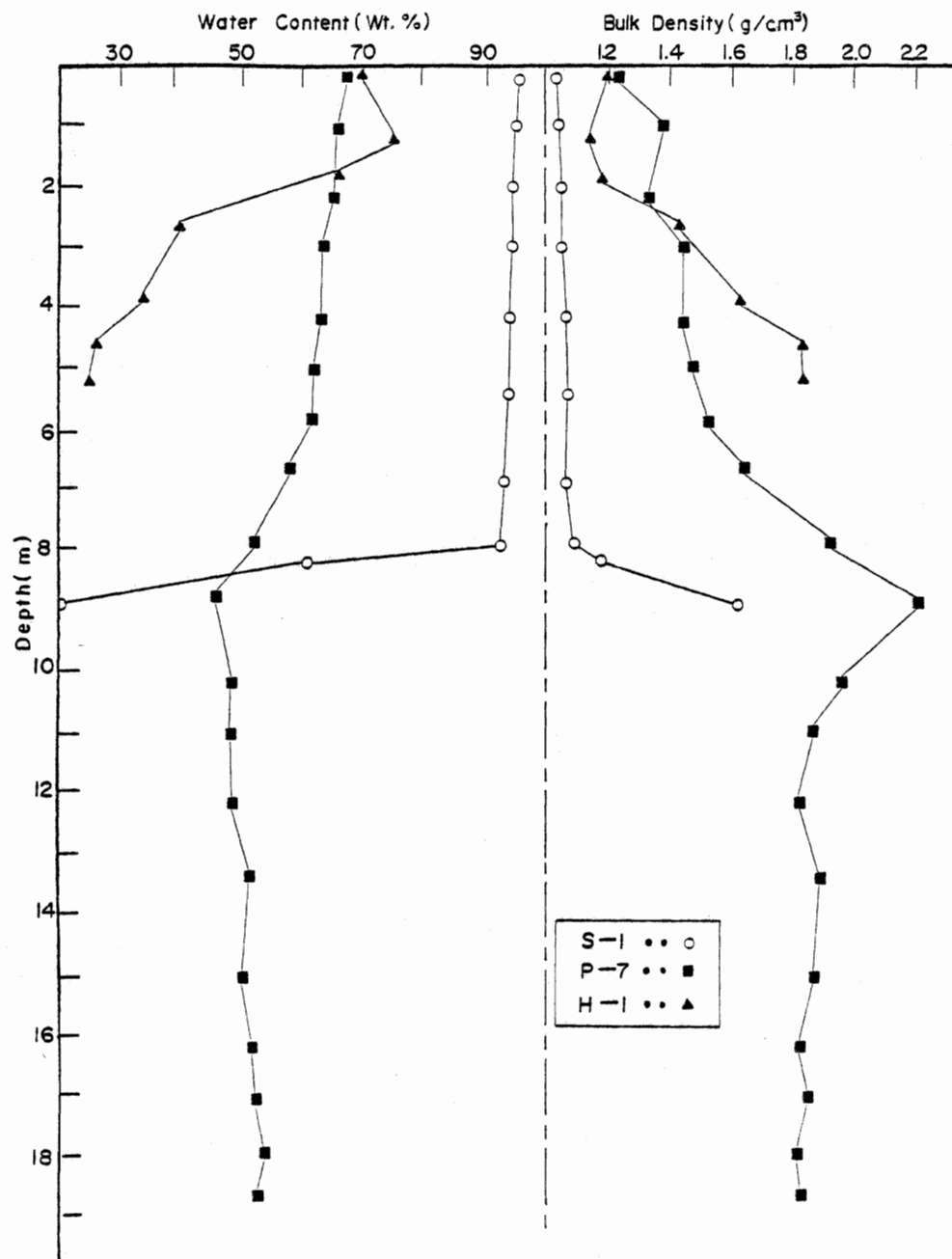


Figure 12. Stratigraphic variations of water content (weight %) and bulk density (g/cm³) of P-7, H-1 and S-1 cores.

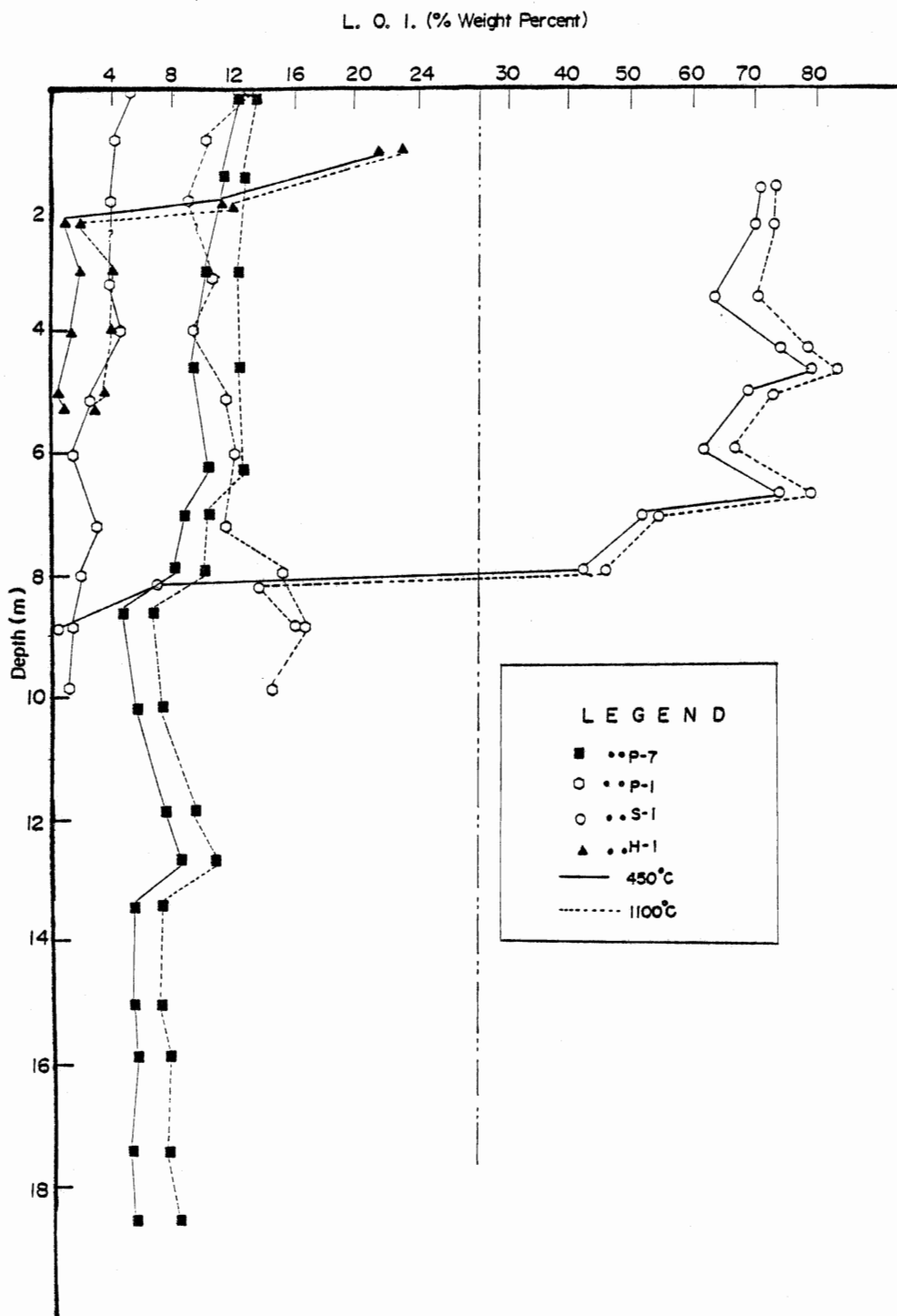


Figure 13. Two loss on ignition measurements of P-1, P-7, H-1, and S-1 cores. L.O.I. is in weight %.

and the sand at the same depth probably just has 45-50% porosity (Fig. 9). As the overlying sediments accumulate and the depth increases, the finer sediments are compacted more rapidly than the coarser sediments, and the relation between grain size and porosity after a certain depth becomes less pronounced (Berner, 1971).

Usually, the porosity versus depth was affected by both composition and compaction. For S-1 core, composition is more important compaction to affect the water content. All the core S-1 down to 780cm was composed of gyttja and the water content decreased slightly from 96.14% to 92.27% due to compaction by overlying sediments. Beginning from 780cm downward, owing to the change of the sediment composition (from gyttja to mud, probably, the mud is composed of quartz, feldspar and clay minerals), the water content drastically decreases from 92.17% to about 20%.

H-1 core has the highest value of 75.74% at 125cm, and then, decreases with increasing depth to about 20% at the core bottom. The highest water content at 125cm depth is the boundary between high or pure organic matter and less organic matter intermixing with very coarse silt (5-10%) and silty clay (the grain size analysis was started at 130cm depth because of high organic matter content)(See APPENDIX II). This anomaly was caused by different rate of compaction and deposition because the water could not be squeezed out if the depositional rate was sufficiently high over a certain period of time. As a result of this, the expulsion of

interstitial water could not keep pace with this rapid increase in compaction, and the amount of the interstitial water in the sediment seemed to be increased and might begin to support an appreciable proportion of the weight of overlying sediments. As a result, anomalously high water content was encountered at 130cm depth and overlying compaction to this boundary (high organic matter/clayey silt) might considerably exceed those expected for simple hydrostatic burial at the same depth. H-1 has a range of water content from 75.74% at 125cm depth to 18.35% at the bottom of the core.

The deposit of clayey sediment in P-7 is much thicker than that of H-1 and the sediment is also more homogeneous (stratigraphy and grain size) than that of H-1. Since the general particle size in P-7 is smaller than H-1, and the water content of P-7 varies within narrow limits, core P-7 could undergo continuous compaction during burial in accordance with the continuous increase of the overlying sediment load. Meade (1966) stated that the influence of particle size on the water content could still be significant at overburden loads approaching  $100\text{kg/cm}^2$ . As the water content of P-7 decreases from 67.84% to 45.08%, and thus the different grain size and compaction should be responsible for controlling the water content within such a narrow range.

The smaller the grain size of the sediment particles, the greater the specific surface area the sediment can reach and the greater the amount of water the sediment can retain (Berner, 1971). Differing from S-1 core, composition is less important than

compaction and grain size for the water content in P-7 core because its stratigraphy and composition are more or less identical and its grain size is small. For example, P-7 core has a minimum water content about 45% at 875cm depth. If we refer to Table 3 for the grain size distribution, the mean grain size is  $7.7\phi$  which is the coarsest of the whole core length. Correspondingly, the water content is low at this depth despite the effect of compaction. Under this condition, grain size controls the water content significantly.

The bulk density of S-1 increases slightly from  $1.03\text{g/cm}^3$  at the top of the core to  $1.10\text{g/cm}^3$  at 780cm. Then, it increases significantly from  $1.10\text{g/cm}^3$  to  $1.62\text{g/cm}^3$  within a short interval of 100cm, caused by the appearance of mud. The bulk density of H-1 ranges from  $1.13\text{g/cm}^3$  to  $2.24\text{g/cm}^3$  and is affected by organic matter content, water content, composition and grain size. Since Harts Lake is small, shallow and more sensitive to its surrounding environment, the bulk density could be increased within a short range of depth by the decrease of water content and organic matter content. From Figure 12, P-7 has its maximum of bulk density at 875cm depth where the lowest water content was obtained. The bulk density of P-7 ranges from  $1.23\text{g/cm}^3$  to  $2.22\text{g/cm}^3$  which is controlled by the same factors -compaction and grain size as in its water content.

The trends of L.O.I. measurement for the three cores (except P-1 core) show a distinct relation with their sediment water

content, grain size, the amount of organic matter and the composition. Generally, their values decrease with increasing depth. As the water content and the grain size have been mentioned already, six X-ray diffraction analyses were selected from Harts Lake at different depths (120cm, 160cm, 220cm, 340cm, 420cm and 520cm) to support the composition factor. Quartz, feldspar, dolomite and calcite showed higher contents at 220cm, 340cm, 420cm, 520cm depths than at 120cm and 160cm depths. Especially at 220cm depth, the highest content of quartz, feldspar and less calcite and dolomite was found. Thus, L.O.I. value ( $1100^{\circ}\text{C}$ ) for H-1 core at 220cm has the lowest value.

For P-7 core, the L.O.I. measurement at  $450^{\circ}\text{C}$  is 12.60% at the top of the core and decreases to 4.61% at 875cm depth. Then, the value increases to 8.50% at about 1280cm and decreases to the bottom of the core. At 875cm depth, the sediment grain size is the coarsest and less organic matter would present as the space of the sediment is small enough to contain sufficient organic matter.

P-1 core has lower L.O.I. values at  $450^{\circ}\text{C}$  when compared with other cores, varying from 5.3% at the top of the core to 1.20% at the bottom of the core. Actually, it decreases with increasing depth, probably due to the depositional environment and compaction of the sediment. The trend of L.O.I. measurement at  $1100^{\circ}\text{C}$  is far different from other cores, ranging from 8.43% (130cm) to 16.49% (885cm), depending on its carbonate content of calcite and dolomite.

All the P-1 samples have greater variance than samples from other cores. The least variance occurs at 130cm depth with a difference 3.54% and the most variance is at 885cm depth with a value 15.13%. All the values are tabulated in Table 5 in detail.

Table 5. Values of water contents, bulk densities, and measurements of loss on ignition at 450° and 1100° of P-1, P-7, H-1, and S-1 cores.

P-1				P-7				H-1				S-1						
Sample	L.O.I. 450° C (%)	L.O.I. 1100° C (%)		Sample	Water%	Bulk Density (g/cm <sup>3</sup> )	L.O.I. 450° C (%)	L.O.I. 1100° C (%)	Sample	Water%	Bulk Density (g/cm <sup>3</sup> )	L.O.I. 450° C (%)	L.O.I. 1100° C (%)	Sample	Water%	Bulk Density (g/cm <sup>3</sup> )	L.O.I. 450° C (%)	L.O.I. 1100° C (%)
#101	5.30	13.16		#701	67.26	1.23	12.60	13.67	# 20	69.89	1.197	10.58	11.77	# 20	95.82	----	-----	-----
#102	4.98	14.26		#703	67.82	1.27	11.52	13.10	# 40	68.64	1.202	10.42	11.66	# 40	96.14	1.03	-----	76.56
#103	4.99	14.71		#704	65.95	1.38	11.94	13.54	# 60	70.09	-----	15.44	16.67	# 60	95.86	1.034	-----	-----
#104	4.24	10.39		#705	65.82	1.36	11.49	12.90	# 80	70.99	1.184	16.53	17.67	# 80	95.43	1.038	-----	-----
#105	5.17	9.06		#706	60.41	1.41	11.41	12.59	#100	73.69	1.163	21.70	22.99	#100	95.07	1.041	-----	83.69
#107	4.89	8.43		#707	65.39	1.34	11.38	13.00	#120	75.74	1.131	-----	18.00	#120	95.42	-----	-----	-----
#108	4.73	10.19		#708	64.50	1.40	10.92	13.09	#140	72.20	1.139	15.39	16.49	#140	95.00	1.044	-----	73.76
#109	4.49	9.37		#709	63.23	1.63	10.27	12.31	#160	67.19	1.142	-----	-----	#160	94.87	1.049	71.08	72.92
#110	4.03	9.32		#710	62.24	1.49	10.57	12.25	#180	65.46	1.172	11.48	11.81	#180	94.98	1.047	-----	-----
#111	3.97	10.86		#712	63.19	-----	10.44	12.41	#200	54.41	1.247	-----	-----	#200	94.92	-----	72.08	75.11
#112	4.27	10.33		#713	61.10	1.53	9.60	12.45	#220	49.25	1.283	1.23	1.96	#220	94.97	-----	70.15	72.91
#113	4.50	9.64		#714	62.19	1.49	10.20	12.86	#240	44.63	1.313	1.45	2.35	#240	95.01	1.047	72.49	76.08
#114	3.83	9.54		#715	59.63	1.86	11.16	14.09	#260	39.65	1.467	1.52	-----	#260	94.83	1.049	-----	-----
#115	4.16	10.30		#718	61.79	1.53	11.82	13.89	#280	43.47	1.319	1.60	3.21	#280	94.76	1.051	70.34	74.07
#116	3.29	10.85		#720	56.41	-----	10.54	12.67	#300	40.08	1.412	1.99	4.12	#300	95.05	1.047	72.11	75.28
#117	2.94	12.86		#722	58.02	1.65	9.45	11.31	#320	38.20	1.244	1.36	3.63	#320	95.00	1.046	-----	72.21
#118	2.59	11.70		#723	53.89	1.87	8.61	10.55	#340	32.33	-----	-----	-----	#340	94.89	-----	64.46	70.22
#119	2.88	11.94		#724	53.24	1.86	8.40	10.41	#360	34.55	-----	1.83	5.82	#360	94.78	-----	-----	-----
#120	2.61	12.83		#726	51.67	1.92	8.18	9.98	#380	34.09	1.649	1.51	3.82	#380	94.92	-----	69.20	72.62
#121	1.45	13.20		#727	47.94	2.20	7.16	9.77	#400	33.89	-----	1.52	4.11	#400	95.04	-----	-----	-----
#122	1.80	12.11		#729	45.08	2.22	4.61	6.70	#420	29.30	-----	1.15	3.43	#420	94.84	1.052	74.22	78.11
#123	1.68	12.07		#731	49.25	1.96	5.36	7.17	#440	34.02	1.665	2.05	6.26	#440	94.60	1.052	-----	75.32
#124	1.58	12.31		#732	50.58	1.89	5.24	7.02	#460	26.51	1.879	1.37	3.47	#460	95.06	1.06	99.83	82.75
#125	1.84	12.05		#733	47.91	1.84	5.49	7.22	#480	29.18	1.708	1.56	5.50	#480	94.72	1.051	77.36	81.89
#126	2.86	11.66		#735	48.30	1.96	5.95	7.43	#500	18.35	2.24	0.54	3.69	#500	94.31	-----	68.71	72.50
#127	2.72	12.59		#736	47.82	1.97	5.91	7.46	#520	25.19	1.831	1.03	3.13	#520	95.20	-----	-----	-----
#128	2.69	11.48		#738	48.09	1.87	5.49	7.17						#540	95.02	1.58	75.37	79.40
#129	3.80	8.61		#739	48.63	1.85	5.95	7.51						#560	94.34	1.06	-----	-----
#130	3.68	9.06		#740	49.20	1.98	7.53	9.38						#580	94.44	1.061	61.47	65.88
#131	3.35	10.04		#741	48.50	1.83	6.99	9.49						#600	95.04	1.057	-----	-----
#132	2.05	15.21		#742	54.08	1.80	8.48	10.72						#620	94.76	1.063	72.46	76.47
#133	2.04	14.02		#743	52.57	1.84	4.88	6.90						#640	94.66	-----	-----	-----
#134	1.89	15.56		#744	50.89	1.9	5.47	7.26						#660	95.59	-----	74.74	78.36
#135	2.06	15.79		#745	51.16	1.89	5.51	7.30						#680	92.96	1.08	-----	-----
#136	1.36	16.49		#747	51.47	-----	5.12	6.95						#700	93.70	1.08	51.61	54.73
#137	1.68	13.31		#748	51.61	1.93	5.37	7.15						#720	92.83	1.08	-----	50.20
#138	1.52	15.74		#749	50.22	1.88	5.42	7.19						#740	94.13	1.09	51.22	53.84
#139	1.74	13.77		#750	51.31	1.96	5.61	7.06						#760	93.09	1.09	-----	57.57
#140	1.20	10.82		#752	51.94	1.94	5.78	7.81						#780	92.27	1.10	42.15	44.68
#141	2.56	10.53		#753	52.12	1.83	5.53	7.17						#800	78.91	1.13	16.34	32.23
#142	2.62	9.93		#754	50.54	1.91	5.52	7.49						#820	61.46	1.19	6.41	13.39
#143	2.39	9.81		#756	52.43	1.86	5.29	7.74						#840	42.15	1.25	0.74	13.89
				#757	54.54	1.78	5.10	7.59						#860	18.39	1.57	0.22	15.74
				#758	52.96	1.81	5.10	7.47						#880	17.08	1.62	0.15	16.06
				#759	53.20	1.76	5.14	7.52										
				#760	52.45	1.83	5.52	8.17										



## GEOCHEMISTRY OF THE LAKE SEDIMENTS

### Some Limnological Comparisons between Harts Lake and Shepherd Lake

Some comparisons of water colour, water transparency, sediment composition, suspended material,.... etc., for these two small lakes are given in Table 6. Both lakes are similar in their size and depth, but are different in respect to bedrock, vegetation and sediment type. On the basis of hydrobiological, sedimentological and limnological conditions, Harts Lake can be defined as a mesotrophic lake and Shepherd Lake as an eutrophic lake.

At first, Shepherd Lake was probably oligotrophic when it was isolated from the glacial lake (Main Algonquin) that covered the Bruce Peninsula. Then, it became eutrophic after the natural inputs of phosphate, carbonate and associated cations from the surrounding Silurian Guelph Formation and Paleozoic carbonate strata. Owing to the nutrient input, Shepherd Lake is characterized by high organic matter production, increased amounts of organic matter and increased sedimentation rate. Simultaneously, additional nutrients such as phosphorous, nitrogen and micronutrients could be released from the lake sediments to supply the need of algal and macrophytic photosynthesis (Wetzel, 1975). Some marl was deposited in Shepherd Lake at 557-576cm

Table 6. Limnological Comparisons between Harts Lake and  
Shepherd Lake

---

Harts Lake	Shepherd Lake
Surface area: 7,000m <sup>2</sup>	4,000m <sup>2</sup>
Bedrock: Precambrian granitic gneiss and migmatite on the Canadian Shield	Paleozoic Silurian Guelph dolomite on the Bruce Peninsula
Water colour: Blue to green	Yellowish or yellow-green
Transparency of water: Good	Fair
Chemical composition of water: Low in nitrate and phosphate	High in phosphate, nitrate and carbonate
Suspension in water: Small amount clayey material and organic matter	Abundant live or dead organic matter (seston)
Sediments: Mainly mineral deposits, some clayey gyttja by littoral vegetation	Mainly gyttja, lake marl and calcareous gyttja
Lake type: Mesotrophic	Eutrophic
Trend of development: Through eutrophic into dystrophic	Into dystrophic

depth. Wetzel (1975) suggested that the deposition of the marl is the result of the sustained input of calcareous matter from the lake's watershed under high pH and  $\text{HCO}_3^-$  condition.

Lake Muskoka, draining into Georgian Bay via Harts Lake, causes the water in Harts Lake to have a higher oxygen content than that in Shepherd Lake. Some sediment in these lakes has been brought in by both direct fluvial transport and surficial runoff. The former is more important for Harts Lake and the latter for Shepherd Lake. The silty clay sediment in Harts Lake is composed of organic matter mixed with varying amounts of mineral matter. The ratio of organic matter to mineral matter increased upward because of the surrounding wetland vegetation. The vegetation could produce abundant organic matter that was transported to the lake (Table 6). Owing to the natural eutrophication, the organic matter produced by the surrounding wetland vegetation could be increased as the deposition continues. The lake basins will be gradually filled with these organic sediment.

The pH measurements of bottom surface sediments in these two lakes at eleven different sites are shown in Figures 14 and 15. The pH values in Harts Lake are slightly acidic whereas Shepherd Lake shows slight alkalinity. Both lakes have lower pH values near the access roads and this probably reflects man's activities. In Harts Lake, samples 1, 6 and 7 have the lowest value with pH=5.8 because pH value could be lowered by the result of the decomposition of organic matter in the swamp area (south-

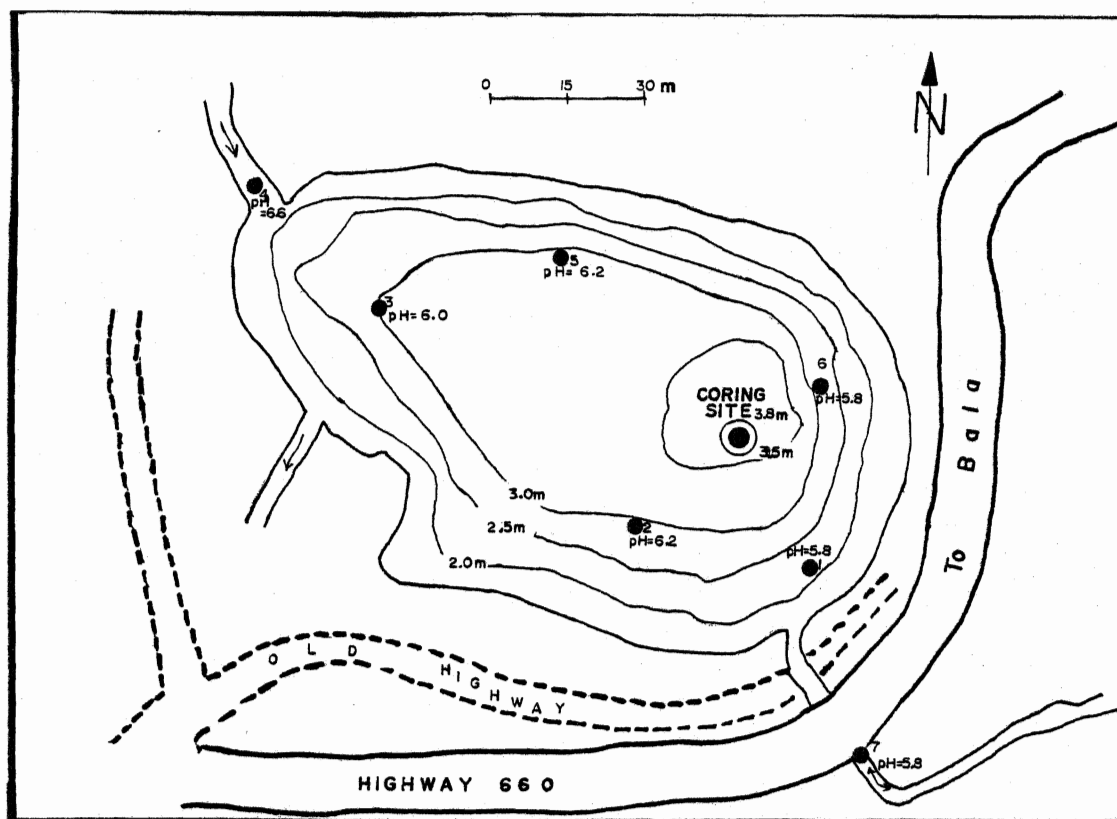


Figure 14. Bathymetry map and location of surface bottom samples of Harts Lake.

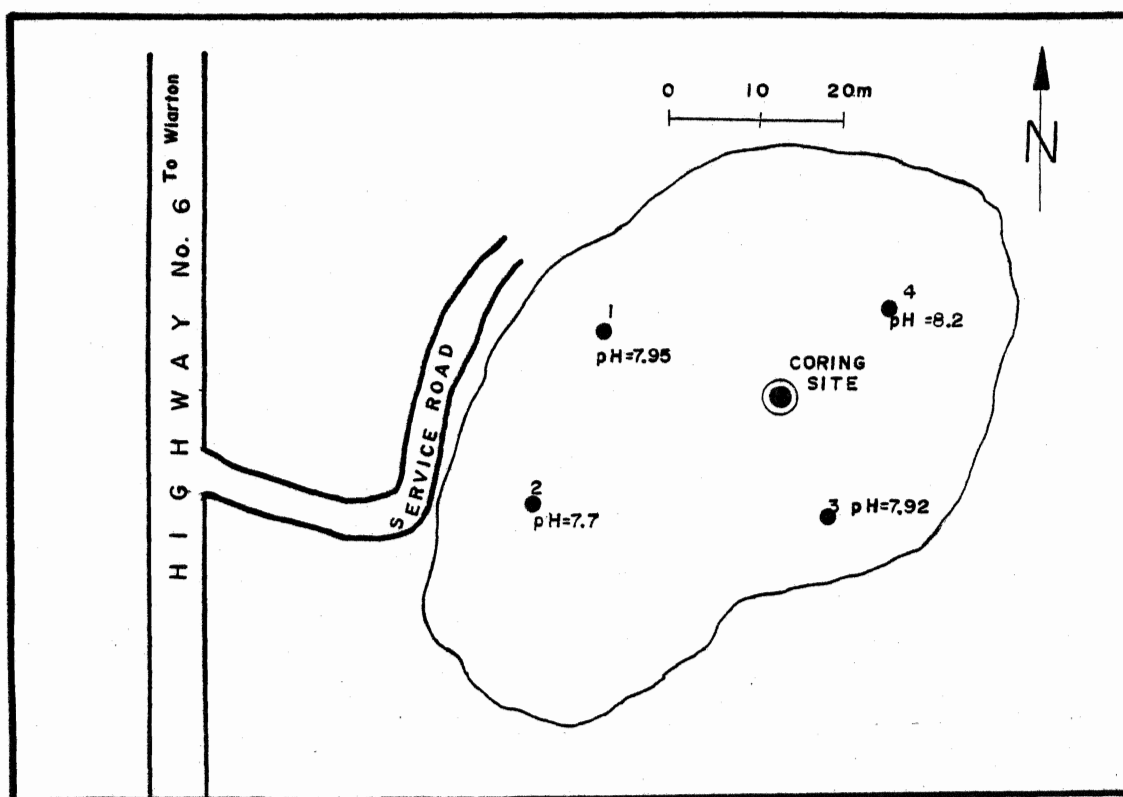


Figure 15. Location of surface bottom samples of Shepherd Lake.

east part of the lake). Besides the influence of the organic matter, all the pH values in Harts Lake are lower than 7 probably due to the acidic precipitation as a result of industrial impact from the north-Sudbury area (Miller, personal comm.).

Kemp et al. (1972) stated that sediment pH can be decreased by decomposition of organic matter and release of  $\text{CO}_2$ ,  $\text{NH}_4^+$  and  $\text{CH}_4$ . As some algal remains, brown humuslike material, and some diatoms could be found in the surface bottom sediment by direct observation, the possible products of decomposition of these are organic acids which are further degraded to  $\text{CO}_2$  and hydrogen (Wetzel, 1975). Methane gas ( $\text{CH}_4$ ) is a further product generated from  $\text{CO}_2$  and hydrogen. All the above-mentioned products can decrease the pH value of the lake sediments significantly.

Krauskopf (1967) stated that if the water of the lake could reach an equilibrium with calcite or dolomite from carbonate rocks, the pH value could reach as high as 10, with average 8-10. Because  $\text{CO}_2$  and  $\text{NH}_4^+$  were produced by decomposition of the organic matter, they could affect the pH value (by their acidic nature) of the lake sediment and pH value could be brought down to 7-8. In Shepherd Lake, pH values range from 7.7 to 8.2, probably owing to the combined effect of the organic matter (which decreases the pH value) and the carbonate bedrock (which increases the pH value of the sediment).

## Geochemistry of Major Oxides

### Results

Table 7 shows the average values of the major oxides from cores P-1, P-7, H-1 and S-1, including the measurement of loss on ignition at  $1100^{\circ}\text{C}$  (presumably, the measurement accounts mostly for the loss of the carbonates at  $1100^{\circ}\text{C}$ ). All the values of the major oxides are expressed by weight percentage. If the total percentages were within the range of  $100 \pm 2.5\%$  (within  $97.5\%-102.5\%$ ), then, the data were considered reliable and applicable. All the original percentages of the major oxides were recalculated back to 100% without L.O.I. measurement, and the results are shown in Table 8.

In the lake sediments studied, chemically,  $\text{SiO}_2$  is the most predominant component of all core samples, followed by  $\text{Al}_2\text{O}_3$  and  $\Sigma\text{FeO}$ . Geographically, each lake has different characteristics for its major oxides distribution and content. For  $\text{SiO}_2$ , H-1 core has the highest  $\text{SiO}_2$  content and the trend decreases westward as  $\text{H-1} > \text{P-7} > \text{P-1}$ . For  $\text{Al}_2\text{O}_3$  and  $\Sigma\text{FeO}$ , P-7 core has the highest values among all the cores studied. For the contents of  $\text{MgO}$  and  $\text{CaO}$ , it seems that P-1 and S-1 cores (from the westside of Georgian Bay) have higher values than P-7 and H-1 (from the east side of Georgian Bay). P-1 core has the highest values of  $\text{K}_2\text{O}$ ,  $\text{MnO}$  and  $\text{TiO}_2$  contents, whereas S-1 core is distinguished by its  $\text{P}_2\text{O}_5$  content. For  $\text{Na}_2\text{O}$ , the

Table 7. Mean values of ten major oxides in the lake sediments of the study areas.

SITE	P-1	P-7	H-1	S-1
NUMBER OF SAMPLES	17	48	17	18
MAJOR OXIDES (%)				
SiO <sub>2</sub>	49.03	58.64	62.22	22.80
Al <sub>2</sub> O <sub>3</sub>	14.03	15.00	13.40	5.38
ΣFeO	6.45	6.96	4.42	1.68
MgO	4.30	2.57	1.77	1.12
CaO	8.64	1.91	2.69	3.33
Na <sub>2</sub> O	0.87	1.26	2.38	0.87
K <sub>2</sub> O	3.57	3.25	2.82	0.85
TiO <sub>2</sub>	0.82	0.80	0.72	0.22
MnO	0.16	0.10	0.13	0.03
P <sub>2</sub> O <sub>5</sub>	0.25	0.43	0.29	0.19
L.O.I.	11.55	10.00	9.67	64.81
TOTAL %	99.67	100.92	100.51	101.28

Table 8. Recalculated values (100%) of Table 7.

SITE	P-1	P-7	H-1	S-1
NUMBER OF SAMPLES	17	48	17	18
MAJOR OXIDES (%)				
SiO <sub>2</sub>	55.65	64.50	68.50	62.53
Al <sub>2</sub> O <sub>3</sub>	15.92	16.50	14.76	14.76
ΣFeO	7.32	7.66	4.86	4.60
MgO	4.88	2.83	1.95	3.07
CaO	9.80	2.10	2.96	9.13
Na <sub>2</sub> O	0.99	1.38	2.62	2.38
K <sub>2</sub> O	4.05	3.57	3.10	2.33
TiO <sub>2</sub>	0.93	0.88	0.79	0.60
MnO	0.18	0.11	0.14	0.08
P <sub>2</sub> O <sub>5</sub>	0.28	0.47	0.32	0.52
TOTAL %	100.00	100.00	100.00	100.00

small lake sediments (S-1&H-1) have relatively higher values than those lake sediments in Georgian Bay (P-1 and P-7).

Comparison of average-valued major oxides from P-1,P-7,H-1 and S-1

Since the geochemistry of the major oxides can best be illustrated on a loss-on-ignition free basis (as stated by Slatt in 1975), in this study, the recalculated averages of the major oxides in Table 8 are used as a background for the comparison.

Berner (1971) stated that quartz is the most resistant among all the minerals from the bedrock to weathering. Since  $\text{SiO}_2$  is a solid residue from the weathering of igneous or metamorphic silicates on the Canadian Shield, its content is thus directly affected by the presence of detrital quartz and feldspar (Eade and Fahrig, 1971; Hewitt, 1967; Shaw et al., 1967). We have assumed that the transporting trend is from east toward west (p. 44),  $\text{SiO}_2$  content decreases along the same trend as H-1>P-7>P-1. Siever (1962), Kukal (1971) and Pettijohn (1975) all suggested that the decrease of the  $\text{SiO}_2$  content is also due to the abrasion and progressive sorting during the transportation and deposition.

Hewitt (1967) reported that in the Harts Lake area diatomite had accumulated in swamps and lakes since the retreat of glacier about 10,000 years ago. The average  $\text{SiO}_2$  content of diatomite in Harts Lake area is about 69.56%, the  $\text{SiO}_2$  content



in the lake sediments could be increased by the presence of diatomite.

Krauskopf (1967) stated that silica could be dissolved in alkaline solution ( $\text{pH} > 8$ ) by presence of some cations ( $\text{Mg}^{++}$ ,  $\text{Ca}^{++}$ ,  $\text{K}^+$ , ...etc.). The  $\text{SiO}_2$  content in S-1 and P-1 cores was relatively decreased due to the presence of these cations mentioned above. We know that the meltwater could also have contributed some carbonate detritus to the lake sediment found in these two cores during deglaciation.

Beside these possible reasons for different  $\text{SiO}_2$  content owing to the carbonate content, S-1 core having a higher  $\text{SiO}_2$  content than P-1 core is due to the following reasons: i) some plants could take up silica from weathering material and release it during decaying (Krauskopf, 1967), and ii) organic matter could be adsorbed on the silica surface and lower its solubility until organic matter was decomposed with subsequent pH change.

$\text{Al}_2\text{O}_3$  content varies in a narrow range and shows that Georgian Bay (P-1 and P-7) has a slightly higher value than the small lakes (H-1 and S-1). Both Williams et al. (1971) and Sly and Thomas (1974) stated that  $\text{Al}_2\text{O}_3$  was derived primarily and secondarily from aluminosilicate minerals. When chemical weathering proceeded, most of inorganic aluminosilicate was attacked slowly by water and  $\text{Al}_2\text{O}_3$  content was not affected

because of its low solubility. Under this condition,  $\text{Al}_2\text{O}_3$  was presumed insoluble and its content varies in a narrow range. In this study, the different  $\text{Al}_2\text{O}_3$  content between Georgian Bay and the small lakes is due to the grain size and the clay mineral content.

Gornitz (1972) suggested that if the clay minerals were formed under a cold climate, its  $\text{Al}_2\text{O}_3$  content was comparable to its original content in the bedrock (e.g.  $\text{Al}_2\text{O}_3$  listed in Table 7 should have similar range to its original content.). Since all the lake sediment samples studied have a similar geographical background during their deposition. Thus, the main difference is owing to its grain size distribution. Coarser grains could have been disintegrated into finer grains by transportational and depositional process into Georgian Bay from the Canadian Shield (and partly from the Bruce Peninsula for P-1) and subsequently more clay minerals could be produced in P-7 and P-1 cores.

$\Sigma\text{FeO}$  content varies between 2.72% and 2.8% among the cores and Georgian Bay has relatively higher value than the small lakes. Pettijohn (1963) reported that organisms whose shells and tests accumulate to form limestone would not contain as much iron as in sandstone and shales. This implies that higher  $\text{CaO}$  content could be expected to decrease  $\Sigma\text{FeO}$  in the lake sediments. Since P-1 and S-1 received certain amount of calcite and dolomite from the Bruce Peninsula and their

$\Sigma\text{FeO}$  contents are lower than P-7 and H-1, respectively. P-1 and P-7 having higher  $\Sigma\text{FeO}$  content than H-1 and S-1 is not clearly known. Possibly, grain size and organic matter could affect its content because smaller grain size could have a higher specific surface area. This phenomenon has been illustrated by Carrol (1958) and Williams et al. (1971).

P-1 and S-1 show higher MgO and CaO contents than P-7 and H-1, and the total difference (MgO+CaO) between the sediments from the Canadian Shield and the Bruce Peninsula is 7.29%-9.25%.

Magnesium minerals from the Canadian Shield are mainly pyroxene, amphibole and biotite, and from the Bruce Peninsula are dolomite and Mg-calcite (Hewitt, 1967; Eade and Fahrig, 1971; Liberty and Bolton, 1971). Pilkey (1972) suggested that CaO is an important mineral constituent in pyroxene, amphibole and feldspar of igneous rock which has an average CaO content about 5.1%. He also suggested that limestone could have a CaO content as high as 42.6%, and sandstone has a much lower CaO content (about 5.5%), as does shale (about 3.1%). Therefore, we know that lake sediments from or near the Bruce Peninsula could have received significant amount of CaO during weathering, transporting and depositional processes.

Thomas et al. (1973) studied the surface sediments in Lake Huron and reported that the carbonate carbon content was

highest in the east region along the Bruce Peninsula (over 3%). They attributed this to either erosion of the bedrock or the shoreline exposure of the carbonate-rich glacial sediments. Dell (1973b) suggested that the carbonate content was influenced by sedimentation rate and in situ dissolution of detrital carbonates.

$\text{Na}_2\text{O}$  content in Shepherd and Harts Lakes is higher than that in Georgian Bay. On the east side of Georgian Bay,  $\text{Na}_2\text{O}$  content is about 0.24%-0.39% higher than that on the west. Short (1961) stated that Na-feldspar of the plagioclase series and possibly NaCl could easily be leached by water during weathering. Consequently,  $\text{Na}_2\text{O}$  content decreased with increasing distance of transport because of its high solubility. Goldich et al. (1959) also suggested that  $\text{Na}_2\text{O}$  content is primarily a function of aluminosilicate and its variation should be in accordance with  $\text{SiO}_2$  content of the sediments. Thus, lower  $\text{Na}_2\text{O}$  content in P-1 and S-1 than in P-7 and H-1 is more or less affected by  $\text{SiO}_2$  content. There is another possibility that anthropogenic loading would contribute certain amount of  $\text{Na}_2\text{O}$  into the lake sediments, especially in Harts Lake and Shepherd Lake.

The  $\text{K}_2\text{O}$  content in the lake sediments was mainly controlled by the amount of K-feldspar from the parent material. Heir and Billings (1972) stated that the weathering of K-feldspar is a function of pH and the concentration of silica and

aluminum in the water. They suggested that  $K_2O$  content would be higher if it was derived under a low pH condition. Probably, this might be part of the reason why H-1 has a higher  $K_2O$  content than S-1. As the  $K_2O$  content increases along the trend as  $H-1 < P-7 < P-1$ , it is also possible that  $K_2O$  is more or less affected by transportational and depositional processes from east toward west.

From Table 8, it is apparent that P-1 and P-7 have higher  $TiO_2$  content (about 0.08%-0.31%) than S-1 and H-1. Sly and Thomas (1974) stated that in the nearshore sediments,  $TiO_2$  shows a good relationship with  $\Sigma FeO$  because of resistant ilmenite ( $FeTiO_3$ ) and/or rutile ( $TiO_2$ ), whereas in the offshore sediments  $TiO_2$  is held by clays. In this study, the  $TiO_2$  content increases mainly proportionally to the corresponding clay content along the sediment transporting direction from H-1 to P-7 and P-1.

Table 8 also shows that P-1 has the highest MnO content and the amount decreases in sequence as H-1, P-7 and S-1. The occurrence of manganese in the Great Lakes Region has been described by Harriss and Troup (1969). In western Georgian Bay, Fe and Mn were found by Sly and Thomas (1974) and no Fe or Mn was found in the eastern region (P-7 core area). This result could explain the Mn occurrence in P-1 core area. Besides, Alexandrov (1972) suggested that MnO content of the lake sediment is inversely proportionally to the organic matter

content which was derived from decaying plants and could move away manganese. The average organic matter contents for P-1, H-1, P-7 and S-1 cores are 3.09%, 3.90%, 7.78% and 52.84%, respectively and their corresponding MnO contents are 0.18%, 0.14%, 0.11% and 0.08%.

Dell (1973a) suggested that phosphorous material occurred in the Great Lakes Region either in organic or inorganic forms. She found that two phosphate minerals were the major sources of inorganic phosphates-i) apatite  $\text{Ca}_5(\text{PO}_4)_3(\text{Fe}, \text{Cl}, \text{OH})$  and ii) vivianite  $\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$ . In this study, vivianite was found in the Georgian Bay sediments (See APPENDIX II). As a matter of fact, 90% of phosphorous material is in organic phosphate and living particulate matter associated with some dead organic material (Wetzel, 1975). As mentioned previously, lake sediments rich in plant fragments and peat detritus (eutrophic lake) could contain more phosphorus than clear lake (oligotrophic lake). The organic matter contents of the four cores in the sequence are S-1>P-7>H-1>P-1 and their corresponding  $\text{P}_2\text{O}_5$  contents are 0.52%(S-1)>0.47%(P-7)>0.32%(H-1)>0.28%(P-1). Thus, phosphorous material in Shepherd Lake is mainly in organic form because of its eutrophic characteristics and in Harts Lake is a mixture of organic and inorganic phosphorous forms.

#### Stratigraphic distribution of individual major oxides

Figures 16, 17, 18 and 19 show the stratigraphic variations

Figure 16. Stratigraphic variations of major oxides versus depth (cm) of P-1.

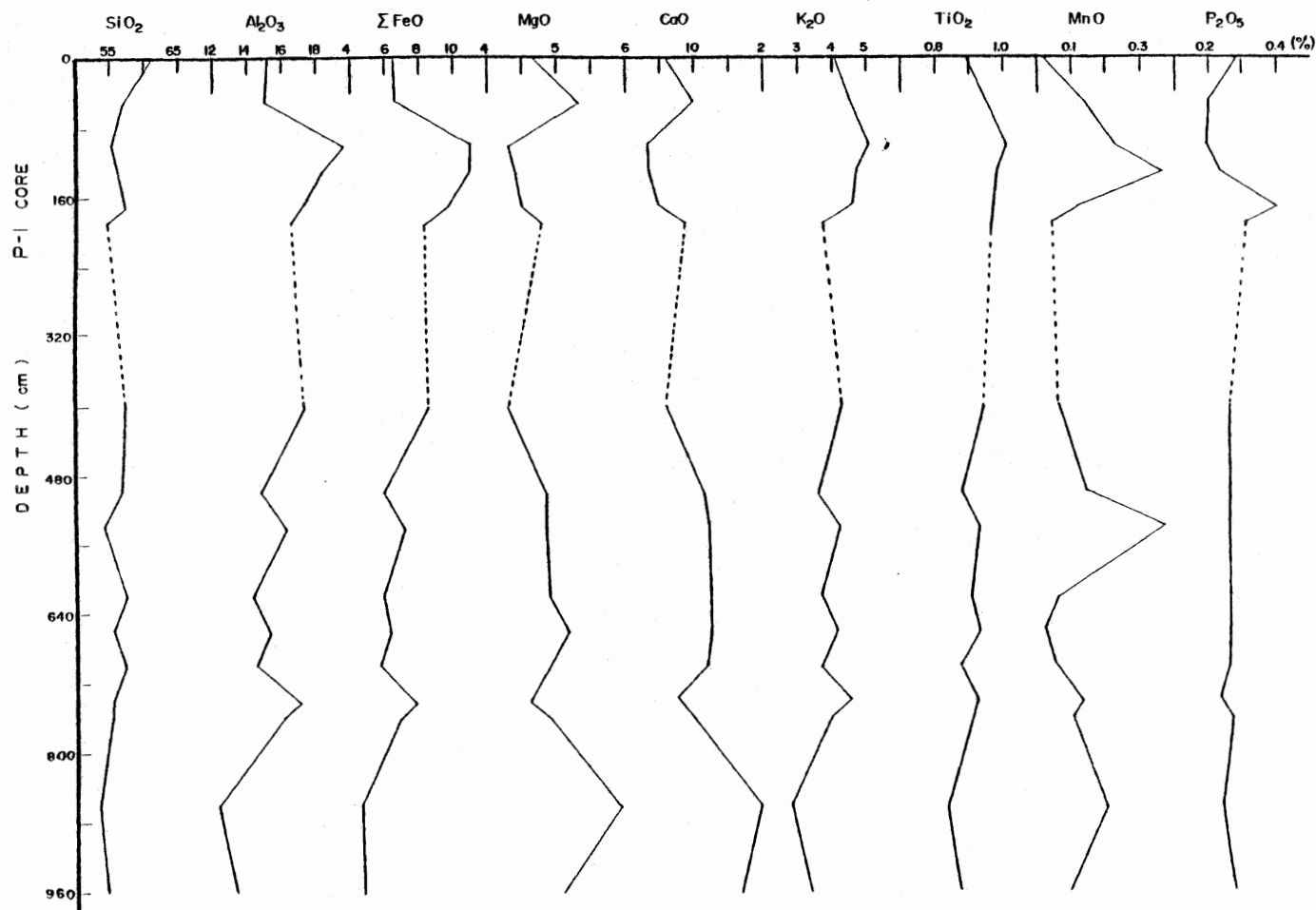


Figure 17. Stratigraphic variations of major oxides versus depth(cm) of P-7.

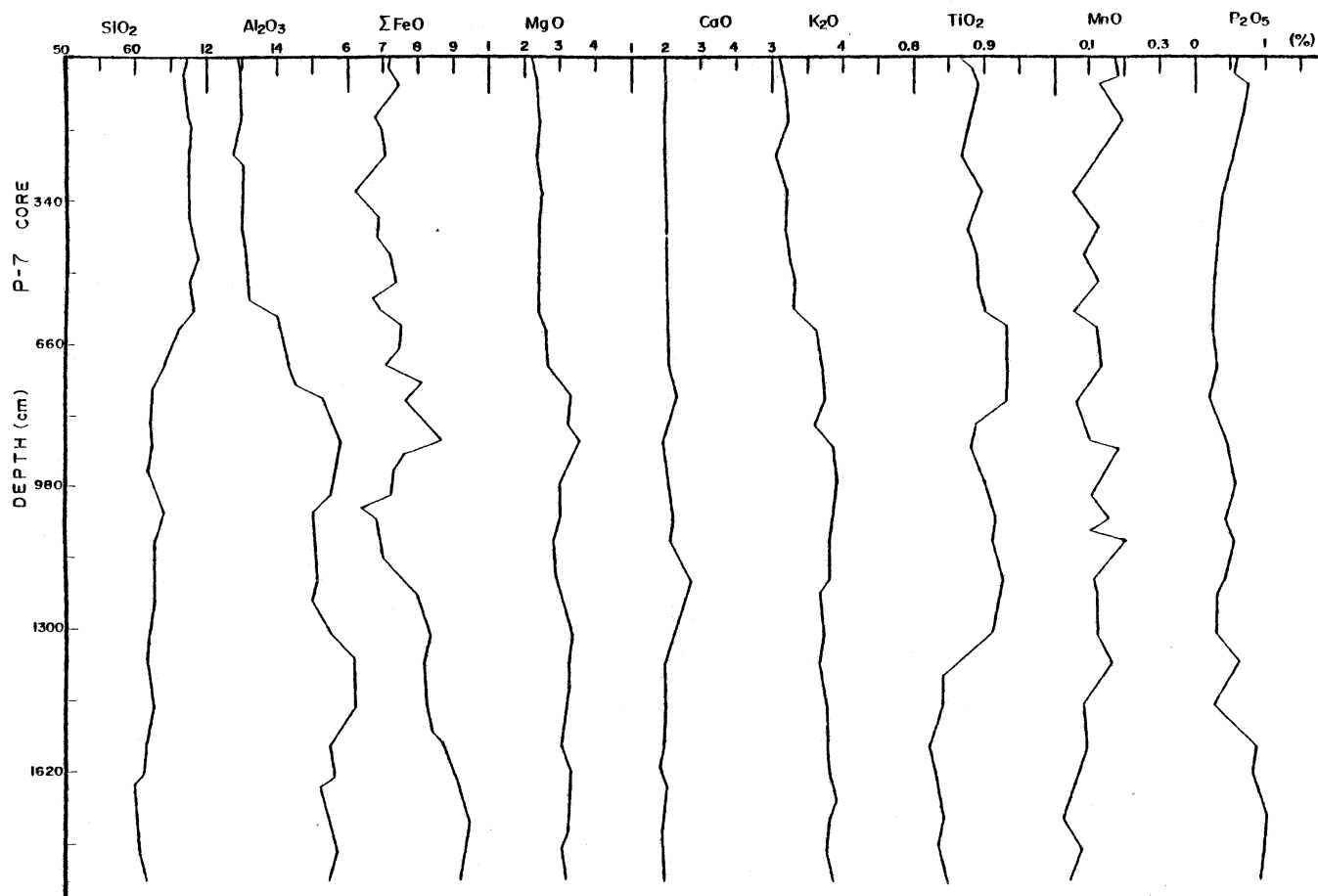




Figure 18. Stratigraphic variations of major oxides versus depth(cm) of H-1.

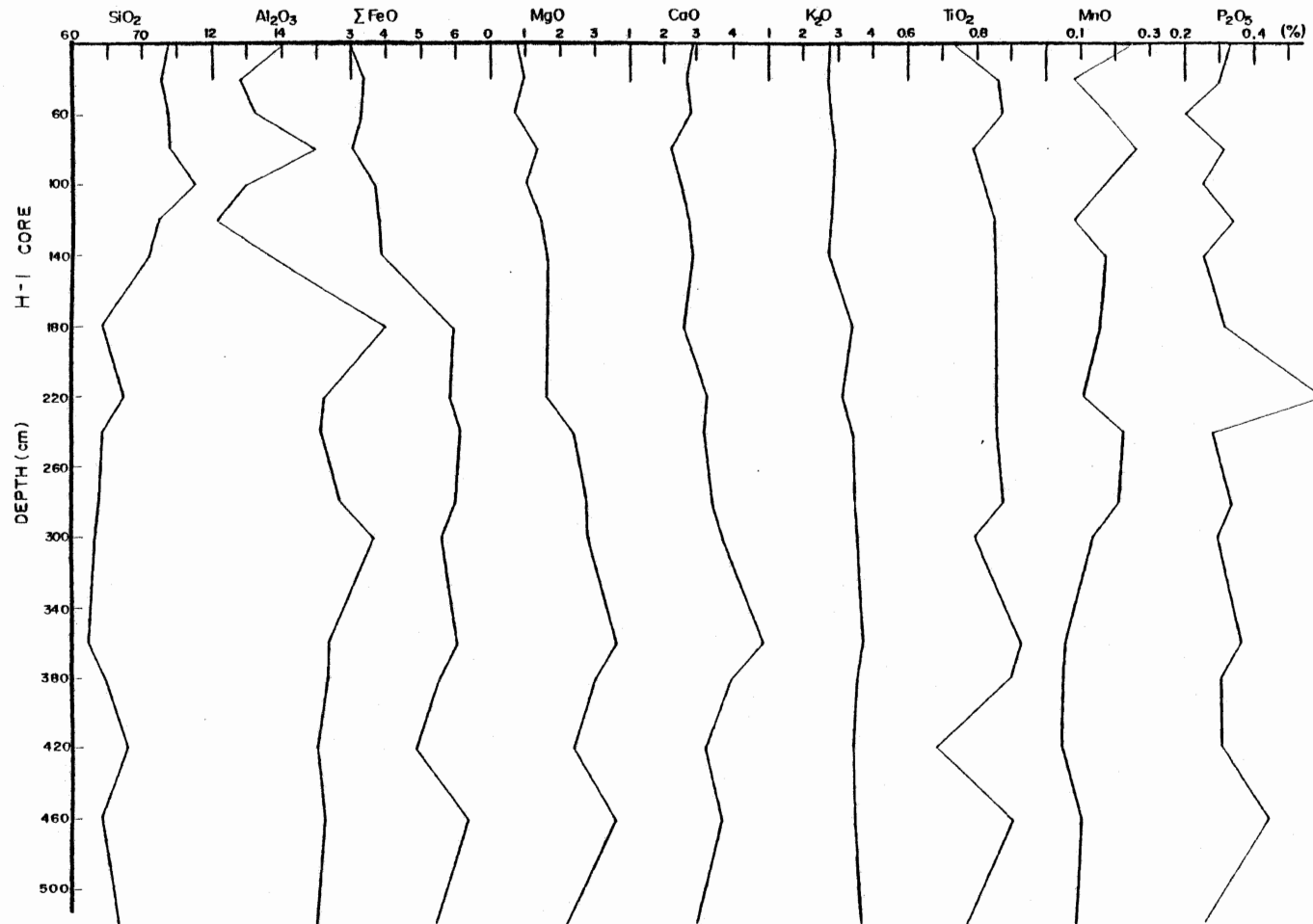
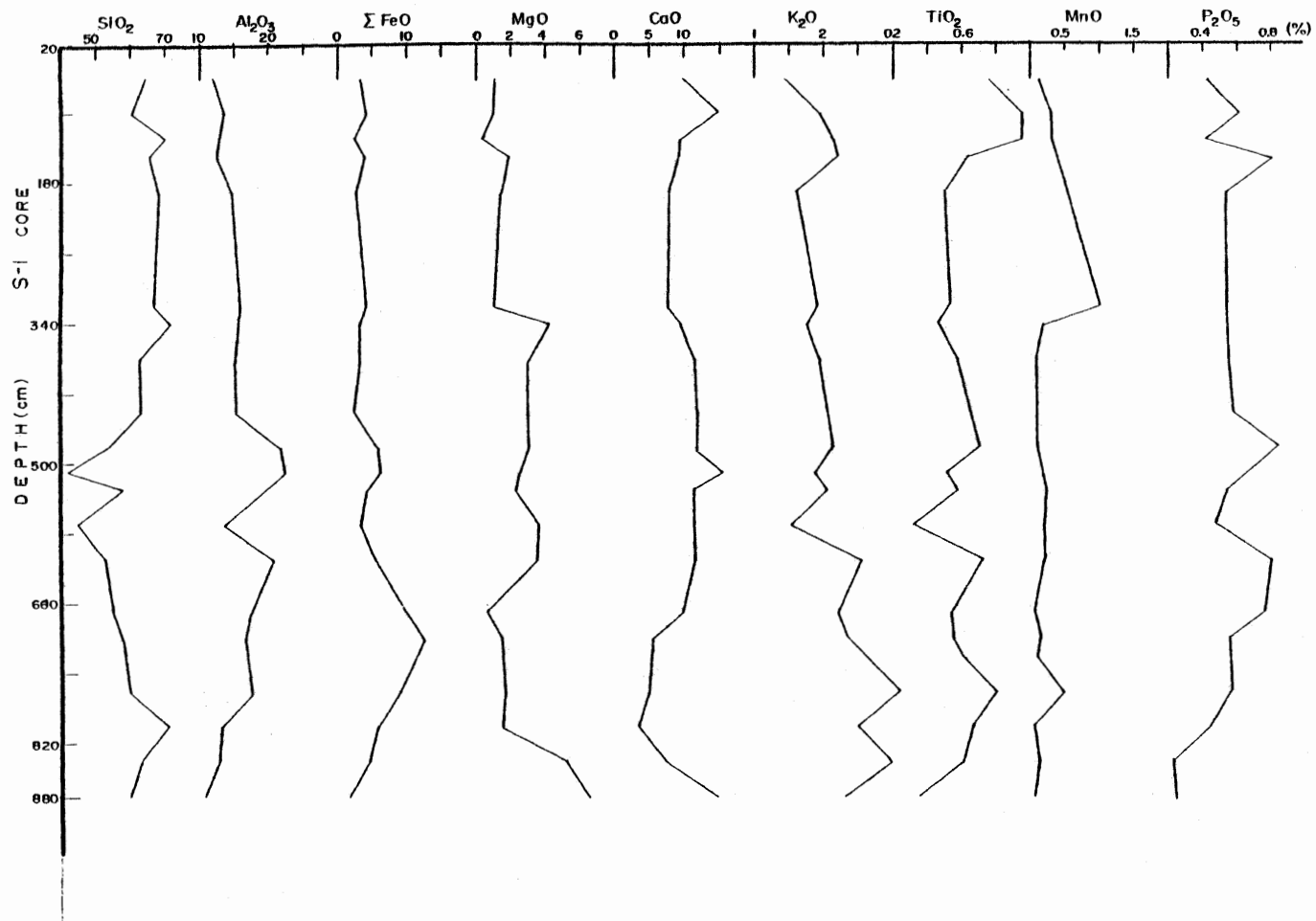


Figure 19. Contents of major oxides vs. depth(cm) of core S-1.



of the major oxides from cores P-1,P-7,H-1 and S-1, respectively. The graph of  $\text{Na}_2\text{O}$  was omitted because the sodium is the lightest element of all the elements analyzed and according to the periodic table, sodium is adjacent to fluorine which is the lower limit of XRF determination. The  $\text{Na}_2\text{O}$  content was highly variable when the same sample was analyzed several times. For example, in Harts Lake,  $\text{Na}_2\text{O}$  content varies from zero to a maximum of 3.84% (at 340cm depth) within a short vertical length of the core. Some results could vary from 40% to 140% of the "mean value" if the same sample was analyzed several times. The reason why we did not discard the discussion of the average-valued  $\text{Na}_2\text{O}$  content is obvious. This is because the average-valued  $\text{Na}_2\text{O}$  content is much more reliable and representative than when it is individually divided.

The following descriptive notes are based on Figures 16,17,18 and 19.  $\text{SiO}_2$  contents of P-1,P-7 and H-1 slightly decrease with increasing depth while  $\text{SiO}_2$  content of S-1 decreases from the top of the core until reaching 570cm and then starts to increase. P-7 has a range of  $\text{SiO}_2$  content from 68.7%(470cm) to 60%(1650cm), and P-1 has its highest  $\text{SiO}_2$  content of 61% at the top, and the lowest content of 53.3% at 860cm depth.  $\text{SiO}_2$  content for H-1 varies from 77.8%(100cm) to 62.5%(360cm). The pattern for S-1 fluctuated within 71.5% (340cm)-42%(510cm) which is the widest range among the four cores.

$\text{Al}_2\text{O}_3$  contents increase with increasing depth for P-7 and H-1, whereas P-1 and S-1 have irregular distribution patterns. P-7 has the lowest  $\text{Al}_2\text{O}_3$  content of 12.9% at the top and the highest content of 16.2% at 1370-1470cm interval. H-1 has a wide range from 12.1%(120cm) to 17%(180cm). P-1 reaches its maximum content 19.7% at 100cm depth and starts to decrease to the lowest content of 12.2%(860cm). S-1 has a narrow range with the lowest content at both ends of the core of 12%(top) and 11%(bottom), and it has the maximum content of 22.5%(510cm).

The trend of  $\Sigma\text{FeO}$  has a rough parallelism with the trend of  $\text{Al}_2\text{O}_3$  in P-1 and S-1. P-7 has a "zigzag" pattern from the top down to 1030cm, with the maximum value of 8.65% (880cm) and the minimum value of 6.2%(320cm). P-1 seems to have a higher  $\Sigma\text{FeO}$  content in the upper part (0-190cm) with its maximum value of 11%(100-130cm) and minimum value of 4.5% (860cm). H-1 has the smallest amount of  $\Sigma\text{FeO}$  of 3% at the top and increases to a maximum of 6.4%(460cm).  $\Sigma\text{FeO}$  reaches its maximum of 12.5%(700cm) and its minimum of 2.5%(130cm) in S-1 core.

The patterns for MgO and CaO contents are closely related in P-1, P-7 and H-1. The CaO content for P-7 shows no variation and the MgO content has a slight increase from 2.2% at the top of the core downward. P-1 has a fluctuating pattern without uniform increase or decrease for both MgO and CaO contents. MgO and CaO contents in H-1 seem to increase

downward. For H-1 core, MgO increases from 0.8% at the top to 3.6% at 460cm depth, and CaO has the maximum of 4.8% at the same depth as MgO. No relationship exists between CaO and MgO in S-1 core, MgO increases from 0.4%(130cm) to 6.4%(880cm), whereas CaO has two higher values of 15%(100cm&880cm) and the lowest content of 3.5% occurs at 800cm depth. The values increased from 800cm downward in S-1 for CaO and MgO was believed either the appearance of mud or the contribution from the bedrock.

The patterns of  $K_2O$  and  $TiO_2$  for P-1 and S-1 show a good trend of parallelism. The  $K_2O$  content of P-7 increases slightly from the top of the core of 3.1% downward to about 3.8% at the bottom.  $TiO_2$  in P-7 increases from 0.87% at the top to 0.93% at 650cm depth, then fluctuate between 0.93% and 0.88% downward to 1200cm. Beyond this depth, the  $TiO_2$  content decreases.  $K_2O$  in H-1 core shows almost no variation and  $TiO_2$  has minor fluctuation.

The  $MnO$  and  $P_2O_5$  contents for all the cores show an irregular patterns with depth, although they seem to decrease slightly with increasing depth. All basic chemical data from these four cores were tabulated in APPENDIX V which includes major oxides, loss on ignition and trace elements.

#### The relationship between the bedrock and the major oxides

During the advance of Wisconsin ice, the bedrock surface

of the Canadian Shield was scoured, polished and abraded by rock particles in the base of the ice. Flint (1971) stated that the rock particles could be moved by: i) scraping and dragging, ii) being enveloped by ice during the ice creeping motion, and iii) being frozen into ice created by refreezing of basal water. The resulting material was deposited in lake basins and on the general landscape, and the lake sediments (either till or glaciolacustrine deposits) are closely related to the components of the bedrock. Since the main ice flowing direction was from north and northeast, the glacial deposits in Georgian Bay were mainly derived from the Canadian Shield, and the bedrock source from the Bruce Peninsula is less significant to affect the characteristics of the lake sediments in Georgian Bay (if compared with the Canadian Shield).

Levinson (1974) stated that the glacial drift on the Bruce Peninsula area is commonly about 5-15m thick and over 20m thick in the southern part of Georgian Bay. He also pointed out that glacial scouring is considered as local event with short distance of transport for the derived bedrock material. The bedrock on the Canadian Shield is predominantly migmatites and granitic gneisses, and their characteristics have been described by Hewitt (1967):

"The migmatitic gneiss is composed of original metasedimentary material with some paragneiss or amphibolite that has been injected, intruded, or permeated by younger granitic material to form a

composite, hybrid, or mixed gneiss. The structure of the migmatite in the Grenville Structural Province could be classified into three types by its banding: banded migmatite, veined migmatite and homogeneous migmatite. About the mineralogy, the migmatite in this area (Parry Sound-Huntsville) consists of microcline, oligoclase, quartz, biotite, and hornblende, with accessory apatite, zircon, titanite, and magnetite, and some times garnet."

Data of the chemical compositions of migmatite (Shaw et al., 1967; Eade and Fahrig, 1971); of granodiorite (as an average of mixed rocks in the study areas on the Canadian Shield) (Nockolds, 1954); of shale and dolomite (Liberty and Bolton, 1971) are listed in Table 9. The relationship between lake sediments and bedrock is described as follows by comparing Table 8 and Table 9.

The chemical composition of the lake sediments is closely related to that of bedrock on the Canadian Shield. However, Shield bedrock has slightly higher values in its  $\text{SiO}_2$ ,  $\text{CaO}$  and  $\text{Na}_2\text{O}$  contents and slightly lower  $\Sigma\text{FeO}$ ,  $\text{MgO}$ ,  $\text{K}_2\text{O}$ ,  $\text{TiO}_2$ ,  $\text{MnO}$  and  $\text{P}_2\text{O}_5$  contents than those values in P-7 core. The decrease of the above-mentioned major oxides ( $\text{SiO}_2$ ,  $\text{CaO}$  and  $\text{Na}_2\text{O}$ ) in the lake sediments are probably the result of weathering and transportation. The decrease of the  $\text{SiO}_2$  content has been discussed previously (p. 76). For  $\text{CaO}$  and  $\text{Na}_2\text{O}$ , Short (1961) and Krauskopf (1967) stated that calcium and sodium from the bedrock source (mainly plagioclase) are relatively soluble and thus their amounts would decrease during the weathering process.

Table 9. Average composition of bedrock from the Canadian Shield and the Bruce Peninsula.

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	ΣFeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	MnO	P <sub>2</sub> O <sub>5</sub>	TOTAL (%)
Nockolds (1954)*	67.32	15.77	3.95	1.58	3.58	3.86	3.09	0.57	0.07	0.21	100.00
Shaw et al. (1967)**	67.67	16.05	4.28	1.89	3.68	3.89	1.78	0.53	0.07	0.16	100.00
Eade & Fahrig (1971)**	66.08	16.16	4.65	2.12	3.43	3.94	2.87	0.51	0.08	0.16	100.00
Liberty & Bolton (1971)***	60.94	19.12	5.74	3.93	3.08	0.17	6.01	0.87	0.06	0.08	100.00
Liberty & Bolton (1971)****	11.94	1.27	0.87	36.08	48.89	0.17	0.61	0.07	0.07	0.03	100.00

\* The average of granodiorite.

\*\* Banded gneisses, migmatite, granitic gneisses and minor amphibolite inclusions.

\*\*\* Shale and dolomite (Cabot Head Formation, restricted).

\*\*\*\* Dolomite (Lockport Formation).



For a further comparison between the bedrock and the major oxides, the CaO/MgO ratios of the four cores and some data from migmatite (Shaw et al., 1967; Eade and Fahrig, 1971) and dolomite from Lockport and Guelph Formations on the Bruce Peninsula (Liberty and Bolton, 1971) are listed in Table 10. From Table 10, we know that the CaO/MgO ratios of the Georgian Bay sediments (P-1 and P-7 cores) are lower than those of the Precambrian Shield and Harts Lake. The CaO/MgO ratios of the Paleozoic bedrock on the Bruce Peninsula are similar to those of P-1 core and lower than those of S-1 core (with a ratio of 3.03). As a whole, the CaO/MgO ratios of the Precambrian Shield are slightly higher than those of the Bruce Peninsula (with a ratio of 1.31).

Harts Lake has CaO/MgO ratios fallen within a range 1.21-2.04 (excluding the Brown core) which are similar to those of the Canadian Shield bedrock. As Harts Lake is entirely surrounded by the Precambrian Shield, its sediment was transported in without much alteration during weathering and transportation, and the CaO/MgO ratios are just slightly changed. Comparing to H-1 core, sediment in P-7 core has been altered more significantly. After the sediment was brought into the Georgian Bay basin, calcium was dissolved much more easily than magnesium due to their different solubilities by water (as illustrated by Krauskopf, 1967), and the ratios decrease. This is the most possible reason why P-7 core has the CaO/MgO

Table 1Q. CaO/MgO ratios of lake sediments in the study areas, and of bedrock from Canadian Shield and Bruce Peninsula (From Shaw et al., 1967; Eade and Fahrig, 1971; and Liberty and Bolton, 1971).

P-7		P-1		H-1		S-1			
Sample Number	CaO/MgO	Sample Number	CaO/MgO	Sample Number	CaO/MgO	Sample Number	CaO/MgO	Sample Number	CaO/MgO
# 701	0.830	# 101	1.456	# HS-1	1.51	# S-60	8.93	* # 249A	1.51
# 703	0.813	# 103	1.951	# HS-2	4.14	# S-100	14.72	# 236A	1.46
# 705	0.824	# 105	0.731	# HS-3	2.32	# S-130	30.22	# 249	1.45
# 707	0.904	# 107	0.769	# HS-4	2.57	# S-150	3.16	# 235A	1.46
# 709	0.843	# 109	1.010	# 100	1.93	# S-190	4.84	# 247	1.51
# 711	0.845	# 111	1.847	# 120	1.82	# S-320	7.31	# 233	1.46
# 713	0.776	# 113	1.400	# 140	1.67	# S-340	2.08	# 234	1.52
# 715	0.849	# 117	2.230	# 180	1.53	# S-380	3.95	# 230	1.44
# 717	0.749	# 119	2.470	# 220	2.04	# S-440	3.93	# 230A	1.43
# 719	0.741	# 123	2.620	# 240	1.26	# S-480	3.71	# 257	1.47
# 721	0.771	# 125	2.370	# 280	1.21	# S-510	6.06	** # 1	1.59
# 723	0.693	# 127	2.620	# 300	1.31	# S-530	5.18	# 2	1.95
# 725	0.740	# 129	1.590	# 360	1.30	# S-610	3.23	# 3	2.26
# 729	0.539	# 131	1.970	# 380	1.40	# S-720	4.90		
# 731	0.694	# 133	3.040	# 420	1.32	# S-760	2.74		
# 735	0.813	# 135	3.320	# 460	1.41	# S-800	2.16		
# 737	0.740	# 139	3.280	# 520	1.39	# S-840	1.39		
# 739	0.749					# S-880	2.29		
# 741	1.300								
# 743	0.664								
# 745	0.625								
# 751	0.620								
# 753	0.566								
# 757	0.580								
# 759	0.603								

\* Data from Liberty & Bolton (1971) - dolomite from the Bruce Peninsula.

\*\* Data from Eade & Fahrig (1971) - migmatite from the Canadian Shield.

ratios less than 1.00. The higher ratios in the Harts Lake Brown core are due to the increasing organic loading and the corresponding increase of CaO content (Hare,1963).

Although P-1 core has similar ratios with those of the bedrock, some CaO/MgO ratios down the bottom of the core are higher. This is probably due to the contribution of limestone from the bedrock by surface and shorebluff erosion (Thomas et al.,1973). Nissenbaum and Swaine (1976) stated that calcium could be adsorbed by the organic matter and its content could be increased subsequently as the organic matter content increased. Because of this, Shepherd Lake has the highest ratios among all the four cores as it had the highest organic matter content (especially in its Brown core). For S-1 core itself, the CaO/MgO ratios decrease downward as the organic matter content decreases.

#### Relationship between individual major oxides

The sediment consisting predominantly of quartz, feldspar, carbonates and clay minerals has already been discussed, and Si,Al,Fe,Mg,Ca and K are the dominant inorganic elements in the sediment matrix. From Table 8, their oxides constitute over 90% of the chemical composition of the lake sediments. The correlation coefficients for these individual major oxides are shown in Tables 11,12 13 and 14 based on the assumption that these oxides have linear relationship and normal distribution.

Table 11. Correlation coefficient matrix for major oxides in P-1 core.

	Al <sub>2</sub> O <sub>3</sub>	ΣFeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	MnO	P <sub>2</sub> O <sub>5</sub>
SiO <sub>2</sub>	-0.05	-0.02	-0.38	-0.30	0.12	N. D.	-0.07	-0.29	0.14
Al <sub>2</sub> O <sub>3</sub>		0.96	-0.75	-0.92	0.11	0.93	0.92	0.43	0.15
ΣFeO			-0.75	-0.92	N. D.*	0.87	0.88	0.55	0.20
MgO				0.84	-0.34	-0.59	-0.54	-0.29	-0.29
CaO					-0.21	-0.88	-0.82	-0.35	-0.20
Na <sub>2</sub> O						0.06	-0.18	-0.14	0.01
K <sub>2</sub> O							0.96	0.29	0.07
TiO <sub>2</sub>								0.35	0.13
MnO									-0.04

\* N. D. = not determined

Table 12. Correlation coefficient matrix for major oxides in P-7 core.

	Al <sub>2</sub> O <sub>3</sub>	ΣFeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	MnO	P <sub>2</sub> O <sub>5</sub>
SiO <sub>2</sub>	-0.82	-0.77	-0.81	-0.19	-0.40	-0.85	0.30	-0.15	-0.45
Al <sub>2</sub> O <sub>3</sub>		0.47	0.81	0.08	0.08	0.92	-0.11	0.09	0.11
ΣFeO			0.60	-0.04	0.17	0.50	-0.61	-0.05	0.50
MgO				0.24	-0.05	0.82	-0.07	0.09	0.23
CaO					-0.06	0.12	0.41	0.11	-0.03
Na <sub>2</sub> O						0.12	-0.30	0.11	0.15
K <sub>2</sub> O							0.92	0.10	0.21
TiO <sub>2</sub>								0.12	-0.22
MnO									-0.01

Table 13. Correlation coefficient matrix for  
major oxides in H-1 core.

	$\text{Al}_2\text{O}_3$	$\Sigma\text{FeO}$	$\text{MgO}$	$\text{CaO}$	$\text{Na}_2\text{O}$	$\text{K}_2\text{O}$	$\text{TiO}_2$	$\text{MnO}$	$\text{P}_2\text{O}_5$
$\text{SiO}_2$	-0.86	-0.91	-0.76	-0.76	-0.67	-0.93	-0.71	0.20	-0.19
$\text{Al}_2\text{O}_3$		0.83	0.57	0.52	0.42	0.77	0.39	-0.28	0.14
$\Sigma\text{FeO}$			0.79	0.62	0.45	0.81	0.56	-0.39	0.39
$\text{MgO}$				0.87	0.29	0.71	0.52	-0.07	0.08
$\text{CaO}$					0.32	0.71	0.66	-0.16	0.33
$\text{Na}_2\text{O}$						0.68	0.74	-0.12	-0.16
$\text{K}_2\text{O}$							0.86	-0.37	0.10
$\text{TiO}_2$								-0.16	0.36
$\text{MnO}$									-0.16

Table 14. Correlation coefficient matrix for  
major oxides in S-1 core.

	$\text{Al}_2\text{O}_3$	$\Sigma\text{FeO}$	$\text{MgO}$	$\text{CaO}$	$\text{Na}_2\text{O}$	$\text{K}_2\text{O}$	$\text{TiO}_2$	$\text{MnO}$	$\text{P}_2\text{O}_5$
$\text{SiO}_2$	-0.77	-0.36	-0.14	-0.58	-0.33	-0.08	0.02	0.19	-0.75
$\text{Al}_2\text{O}_3$		0.44	-0.10	0.31	0.04	0.04	0.07	N. D. *	0.74
$\Sigma\text{FeO}$			-0.22	-0.45	0.01	0.64	0.25	0.08	0.30
$\text{MgO}$				0.31	-0.03	0.19	-0.59	-0.25	-0.14
$\text{CaO}$					0.17	-0.46	-0.13	-0.31	0.41
$\text{Na}_2\text{O}$						-0.33	-0.18	-0.19	0.39
$\text{K}_2\text{O}$							0.95	0.14	-0.16
$\text{TiO}_2$								0.06	-0.01
$\text{MnO}$									-0.08

\* N. D. = not determined

These correlation coefficients were calculated to find out the relationship between individual major oxides under similar weathering, transportational, erosional and depositional processes. Generally, they are considered to be significant if their values are higher than +0.60 or lower than -0.60.

In Table 11,  $\text{SiO}_2$  has low correlation coefficient if compared with all other major oxides and this is in agreement with the conclusion by Kemp et al. (1976). They have no positive interpretation for this phenomenon. In this study, it is probably due to the mixed  $\text{SiO}_2$  contribution from the Canadian Shield and the Bruce Peninsula.  $\text{Al}_2\text{O}_3$  has significant correlation coefficient with  $\Sigma\text{FeO}$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{K}_2\text{O}$  and  $\text{TiO}_2$ . As aluminum is indicative of the clay mineral content, the relationship of  $\text{Al}_2\text{O}_3$  to  $\text{K}_2\text{O}$  confirms the dominance of illite (60%) in the lake sediments. For the clay mineral content, Kemp et al. (1976) reported that the clay minerals in the Great Lakes Region contain more illite (70-80%) than chlorite and kaolinite. In this study, about 60% illite, 30% chlorite and 10% kaolinite were found by XRD analysis.

For  $\Sigma\text{FeO}$ , it also shows high correlation coefficient with  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{K}_2\text{O}$  and  $\text{TiO}_2$ . The reason for this correlation is not clearly known, probably it is affected by the clay mineral content and the grain size (Thomas, 1969a; Kemp and

Thomas, 1976).

Kemp et al. (1976) found that MgO and CaO show a good positive relationship with the silt-size fraction and a negative relationship with the clay-size fraction. Moreover, they calculated the correlation coefficients between  $\text{Al}_2\text{O}_3$  and MgO in Lake Erie sediments as -0.667 which is lower than that in P-1 core ( $r=-0.75$ ). MgO and CaO in sediments usually represent detrital carbonates in silt-size fraction (Dell, 1973b), whereas  $\text{Al}_2\text{O}_3$  and  $\text{K}_2\text{O}$  are indicative of the clay minerals and  $\Sigma\text{FeO}$  is positively related to  $\text{Al}_2\text{O}_3$  ( $r=0.96$ ). For this reason, they have negative correlation coefficients for  $\text{Al}_2\text{O}_3$  vs. CaO,  $\text{Al}_2\text{O}_3$  vs. MgO,  $\Sigma\text{FeO}$  vs. CaO,  $\Sigma\text{FeO}$  vs. MgO,  $\text{K}_2\text{O}$  vs. CaO and  $\text{K}_2\text{O}$  vs. MgO. High correlation coefficient between CaO and MgO ( $r=0.84$ ) suggests that the carbonate mineral in the core sediments with high calcium and magnesium contents was derived from the Paleozoic strata on the Bruce Peninsula (Kemp et al., 1976; Thomas et al., 1973).

$\text{SiO}_2$  has better correlation coefficients with other major oxides (except CaO) in P-7 core than in P-1 core. As Tables 7 and 8 were compared, the chemical composition of P-7 sediments has been altered slightly after weathering, transportation and deposition. Thus,  $\text{SiO}_2$  in sediment could still maintain close relation with other major oxides. Of course, Harts Lake has better correlation coefficients than P-7 core

by its characteristics. The lower correlation coefficients in P-7 core (if compared with H-1 core) for CaO and Na<sub>2</sub>O is probably affected by the solubility and the organic matter.

Uzdowski (1972) stated that the Mg-minerals in bedrock (mainly pyroxene, amphibole and biotite) are decomposed in a similar way as feldspar and the reaction to weathering for Al and Mg are almost similar. Probably, this is why Al<sub>2</sub>O<sub>3</sub> vs. MgO has a high correlation coefficient in P-7 core. Al<sub>2</sub>O<sub>3</sub> vs. K<sub>2</sub>O in Table 12 also shows high positive relationship (r=0.92) which is similar with P-1 core (r=0.93)(Table 11) and higher than H-1 core (r=0.77)(Table 13).

Figures 20 and 21 show the relation between major oxides for four core samples. Among these, TiO<sub>2</sub> has the highest correlation coefficient with K<sub>2</sub>O for all the core samples. Degens (1965) suggested that it is because titanium could be bound in the clay lattice during the weathering processes. Kemp et al. (1976) also confirmed this conclusion by studying Lake Erie sediments which have a correlation coefficient with r=0.64.

K<sub>2</sub>O and MgO in P-7 core and K<sub>2</sub>O in P-1 core have statistically significant increase with increasing TiO<sub>2</sub>,  $\Sigma$ FeO and Al<sub>2</sub>O<sub>3</sub>. Slatt (1975) stated that this is due to increasing clay mineral content. MgO has a decrease with increasing  $\Sigma$ FeO and Al<sub>2</sub>O<sub>3</sub> amount. Kemp et al. (1976) attributed this to



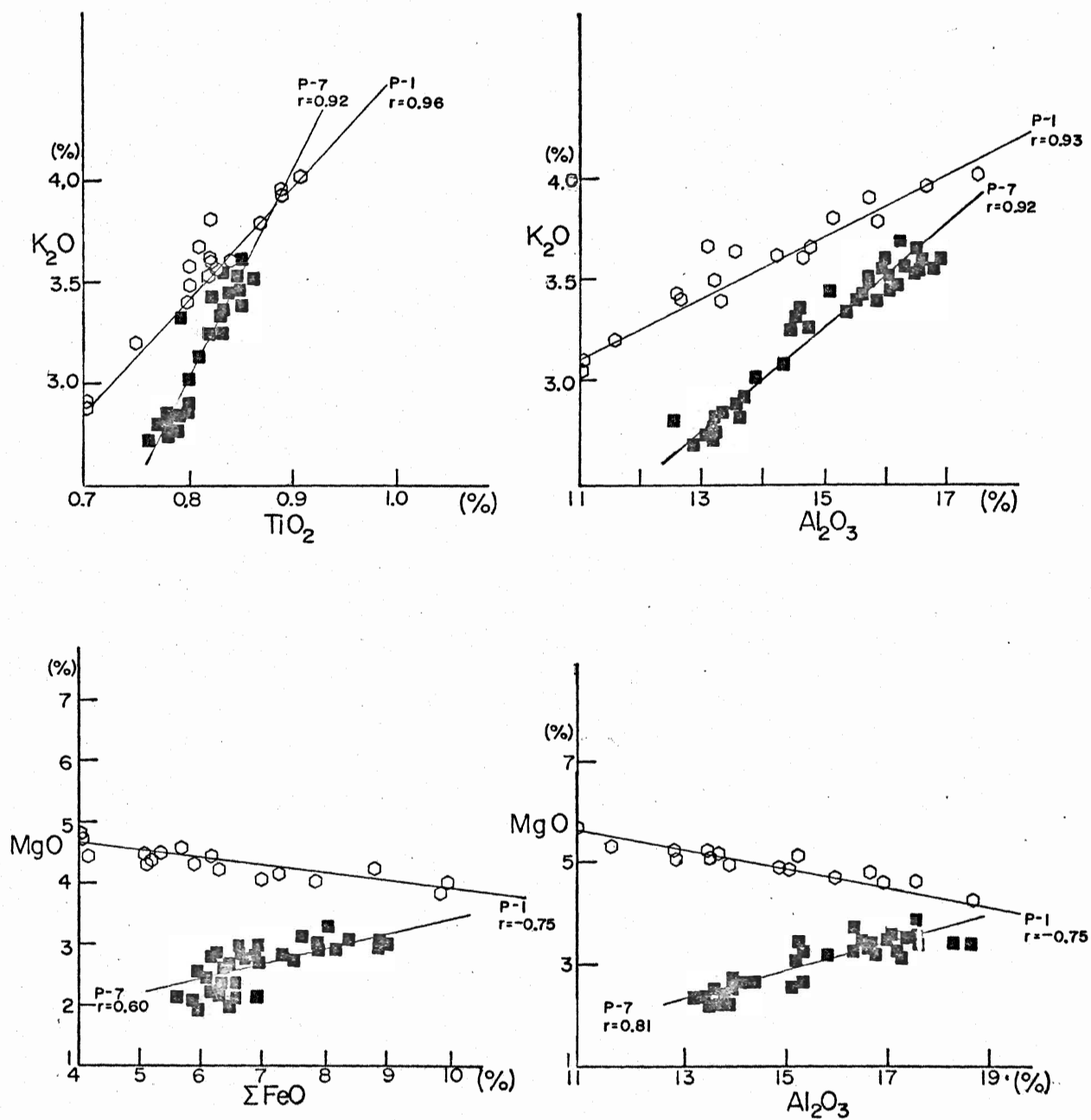


Figure 20. Relationship of  $TiO_2$  vs.  $K_2O$ ,  $Al_2O_3$  vs.  $K_2O$ ,  $\Sigma FeO$  vs.  $MgO$  and  $Al_2O_3$  vs.  $MgO$  in P-1 and P-7 cores.

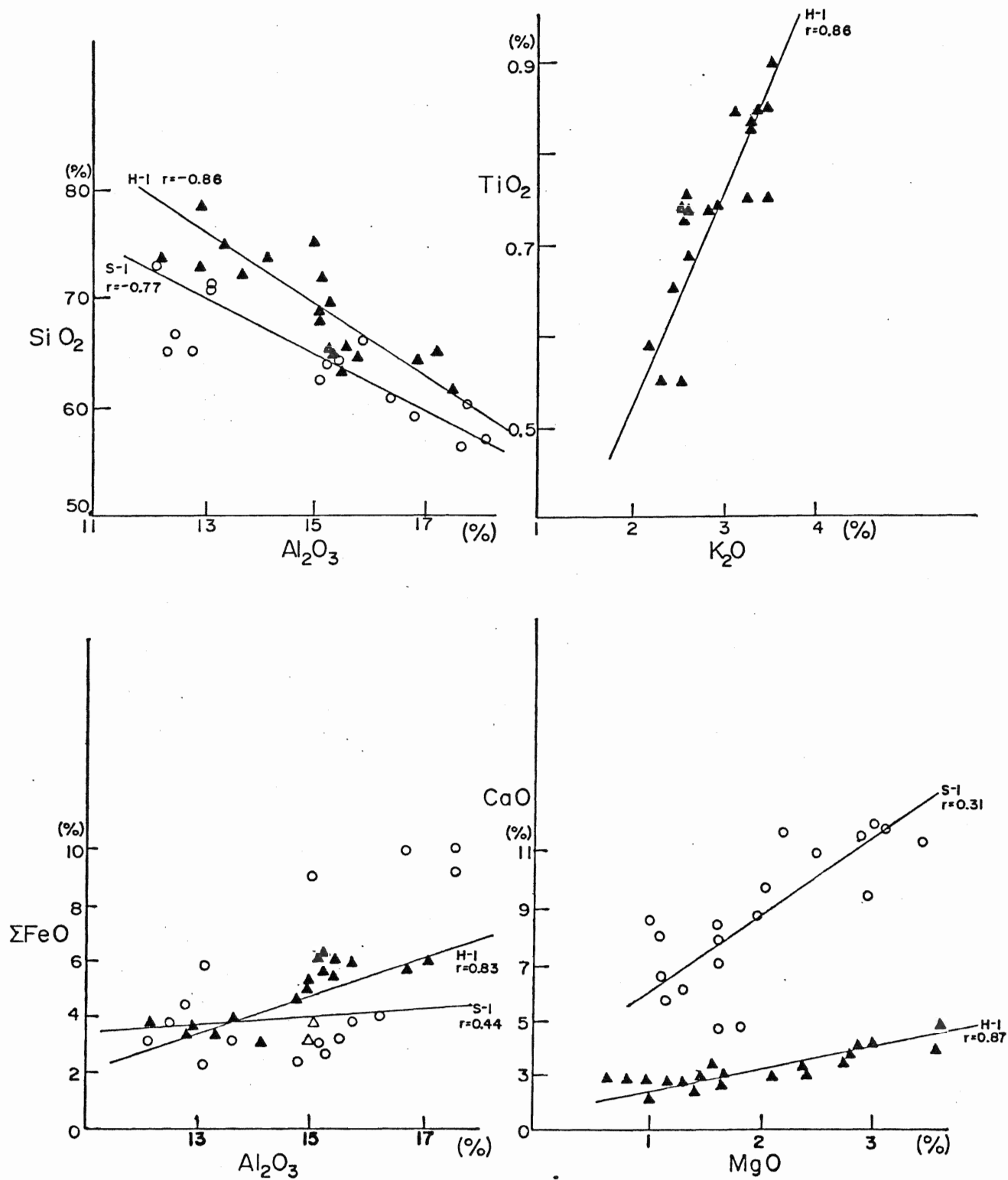


Figure 21. Relationship of Al<sub>2</sub>O<sub>3</sub> vs. SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> vs. ΣFeO, and MgO vs. CaO in H-1 and S-1 cores.

the contribution of Mg by detrital dolomite into silt-size fraction.

$\text{SiO}_2$  in Figure 21 shows a decrease with increasing amount of  $\text{Al}_2\text{O}_3$  for both H-1 and S-1 cores. This is in agreement with the conclusion reached by other authors (Slatt,1975;Kemp and Thomas,1976;Kemp et al.,1976). The decrease in  $\text{SiO}_2$  content is attributed to progressive dilution by weathering processes (Slatt,1975).  $\text{TiO}_2$  vs.  $\text{K}_2\text{O}$  has the same reasoning as for P-7 and P-1 cores. The increase in  $\text{FeO}$  content with increasing  $\text{Al}_2\text{O}_3$  is also in agreement with the result in other Great Lakes sediments. Probably, it is closely related to the clay mineral content and the grain size (Slatt,1975). The high correlation coefficient of  $\text{CaO}$  vs.  $\text{MgO}$  reflected their relationship originally in the bedrock (as illustrated by Slatt,1975).

#### Relationship between major oxides and organic matter

The organic matter input to Georgian Bay basin and the small lakes in its vicinity after deglaciation is an index reflecting the actual landscape that is subject to weathering and transportational processes. Although some increase of the organic matter content upward in the cores is also due to natural eutrophication and anthropogenic loading, the organic matter content is mainly related to the distribution and density of the vegetation in the lake's watershed.

The correlation coefficient matrices among major oxides, organic matter and clay-size fraction are shown in Table 15. Among the major oxides, some of the better correlation coefficients are related to  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\Sigma\text{FeO}$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{K}_2\text{O}$ ,  $\text{TiO}_2$  and  $\text{MnO}$  of P-1;  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\Sigma\text{FeO}$ ,  $\text{MgO}$  and  $\text{K}_2\text{O}$  of P-7;  $\text{SiO}_2$ ,  $\Sigma\text{FeO}$ ,  $\text{MgO}$ ,  $\text{CaO}$  and  $\text{K}_2\text{O}$  of H-1; and  $\text{Al}_2\text{O}_3$ ,  $\text{K}_2\text{O}$  and  $\text{P}_2\text{O}_5$  of S-1. Organic matter content showing a positive relationship with clay-size fraction was found in Great Lakes (Thomas et al., 1972, 1973; Sly and Thomas, 1974; Thomas et al., 1976) and small lakes in glaciated terrain (Scholette and Friedman, 1973), with a rough proportional relationship with the clay mineral (illite) content. Kemp et al. (1976) found that the relationship between organic matter and clay-size fraction is always significant. Owing to the natural eutrophication and the increasing organic carbon loading of the sediment with time, the relationship between them could be changed.

Although the grain size of each core was analyzed, the substantial clay fraction is still not clearly known because of the accuracy of the Quantimet. From Table 15, the relation between organic matter and clay-size fraction was not clear, and only S-1 core has significant correlation coefficient. Here, discussion has been focused only on the organic matter content and its relationship with major oxides. The sequence of clay-size fraction as P-1>P-7>H-1 was applied only as a rough guide.

Table 15. Correlation coefficients among major oxides, organic matter, and clay-size fraction

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	ΣFeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	MnO	P <sub>2</sub> O <sub>5</sub>	Clay fraction
P-1	0.638	0.981	0.764	-0.758	-0.892	0.223	0.701	0.608	0.827	0.116	0.421
P-7	0.925	-0.958	-0.634	-0.793	0.020	-0.338	-0.891	0.221	0.319	-0.215	0.573
H-1	0.799	-0.562	-0.778	-0.712	-0.679	----	-0.868	0.581	0.182	-0.326	0.482
S-1	-0.482	0.834	0.156	-0.440	0.215	0.020	0.709	0.332	0.250	0.697	0.602

Nissenbaum and Swaine (1976) proposed two possible combinations between major oxides and organic matter:i) the elements of major oxides were transported with an initially much larger amount of organic matter from their source;ii) the elements of major oxides were leached out from some mineralogical components and subsequently combined with organic matter. In addition, they found that if the organic matter is produced by some bacterial action, pH and oxygen concentration in the sediment will then decrease and the solubility of these elements of major oxides will increase.

Krauskopf (1967) and Nissenbaum and Swaine (1976) stated that organic matter could play a major role in the geochemistry of dissolved silica by adsorbing silica, and their association is a natural phenomenon. In this study, we also conclude that organic matter is closely related to the  $\text{SiO}_2$  content except for S-1 core. P-7 and H-1 cores have higher correlation coefficients between  $\text{SiO}_2$  and organic matter than P-1 and S-1 cores. On the east side of Georgian Bay, lake basins could receive their allochthonous supply of organic matter from the forest in the watershed and only a small amount from the west because of poor surface drainage. S-1 core has a negative correlation coefficient ( $r=-0.482$ ) of  $\text{SiO}_2$  vs. organic matter and the reason is not clear. Probably, some silica could have been brought to the Shepherd Lake basin by dissolution of

diatom frustules after its isolation at the close of the Lake Algonquin stage. Since Shepherd Lake is an isolated lake, this input could disturb the ratio of  $\text{SiO}_2$  and organic matter contents, and consequently, the correlation coefficient is less significant.

Unlike P-1 and S-1 cores,  $\text{Al}_2\text{O}_3$ ,  $\Sigma\text{FeO}$  and  $\text{K}_2\text{O}$  have negative correlation coefficients with organic matter in P-7 and H-1. Kukal (1971) studied the Lake Punnus-Jarvi in Karelia, Finland, regarding the iron content in sediments, and noted that the temperature and oxygen content decreased with increasing depth, whereas  $\text{pH}$ ,  $\text{HCO}_3^-$  and  $\Sigma\text{FeO}$  decreased distinctly. As Al and K are indicative of the illite content and Fe is derived from hydroxides (Sly and Thomas, 1974), some dissolution and migration of Fe could occur in the interstitial water, and they were accumulated by the decrease of organic matter (Kemp et al., 1976). S-1 has a low correlation coefficient between  $\Sigma\text{FeO}$  and organic matter probably due to high mobility of iron element within the gyttja which has extremely high water content.

$\text{CaO}$  and  $\text{MgO}$  contents have an inverse relationship with organic matter in these cores studied and S-1 core has the lowest correlation coefficients. Probably, extremely high organic matter content in S-1 core causes this result. Na is a highly soluble element and the amount of Na is also variable and the values of correlation coefficients are generally low in Table 15.

Owing to the distribution behaviour of titanium during weathering, it is controlled by mechanical disintegration, and higher organic matter content would relatively diminish the correlation coefficients (Yaalon et al., 1974). Thus, P-1 and H-1 have higher values than that of P-7 and S-1. Mn distribution and its relationship with organic matter is only significant in P-1 and the reason is not clearly known.

Williams et al. (1971) suggested that phosphorus in sediment is bound up with organic matter which is independent of aluminum and iron contents of the sediments. Kemp et al. (1976) stated that the significant correlation between phosphorus and organic matter is due to the natural eutrophication and commensurate increase in organic matter. Besides these, S-1 core having the highest correlation coefficient ( $r=0.897$ ) among these cores is probably because over 90% of its phosphorous content in lake sediment derived from organic origin (as illustrated by Williams et al., 1971).



## Geochemistry of Trace Elements

### Results

The detailed results of individual analyses of trace elements are presented together with major oxides and loss on ignition in APPENDIX V and the minimum, mean and maximum values of the concentrations (of the trace elements) (in ppm) are described in Table 16. For the mean concentrations of the trace elements, P-1 core has lower values than P-7 core for every elements. Comparing P-7 and H-1 cores, barium, zirconium, strontium and cerium in H-1 core are higher and yttrium, sulphur, zinc, copper, nickel and rubidium are lower in H-1 than that in P-7. Except zinc, copper, nickel and rubidium, the mean concentrations in P-1 core are lower than that in H-1 core.

Stratigraphically (from the top of the core downward), in P-1, strontium and zirconium increase, rubidium, nickel, copper and zinc decrease, and the others remain relatively unchanged with increasing depth (Fig.22). In P-7, barium and rubidium increase, and the remaining elements are roughly unchanged with increasing depth in the profile (Fig.23). In H-1 core, barium and rubidium increase, zinc and zirconium decrease, and the remaining elements (excluding sulphur) vary in a narrow range with increasing depth (Fig. 24). The fluctuations in trace elements concentration may represent variable sediment inputs (Kemp et al.,1976) or in part be due to

Table 16. The ranges and mean values of trace elements concentrations in the lake sediments

SITE		P-1	P-7	H-1
NUMBER OF SAMPLES		32	60	24
TRACE ELEMENTS ( ppm )				
Ba	Maxi.	659.7	743.6	1085.7
	Mean	571.5	582.6	783.1
	Mini.	426.2	386.4	344.0
Zr	Maxi.	183.1	190.5	536.0
	Mean	143.0	167.1	325.2
	Mini.	123.0	147.7	218.2
Sr	Maxi.	321.3	236.4	349.3
	Mean	199.8	206.8	295.4
	Mini.	129.4	183.8	233.8
Y	Maxi.	29.4	30.1	29.4
	Mean	26.8	28.5	27.9
	Mini.	22.1	27.0	24.5
S	Maxi.	1627	4079	6643
	Mean	1004	1919	1465
	Mini.	363	428	76
Zn	Maxi.	115.4	119.4	142.7
	Mean	83.9	106.2	82.3
	Mini.	46.5	93.7	25.0
Cu	Maxi.	45.3	66.4	84.8
	Mean	31.3	47.6	23.1
	Mini.	12.4	32.0	7.4
Ni	Maxi.	78.1	74.8	69.9
	Mean	60.1	67.5	44.4
	Mini.	32.2	61.4	19.8
Rb	Maxi.	141.1	132.1	98.9
	Mean	93.7	111.2	68.8
	Mini.	68.1	65.2	48.7
Ce	Maxi.	95.6	127.9	158.0
	Mean	72.3	85.1	93.9
	Mini.	25.5	48.6	66.7

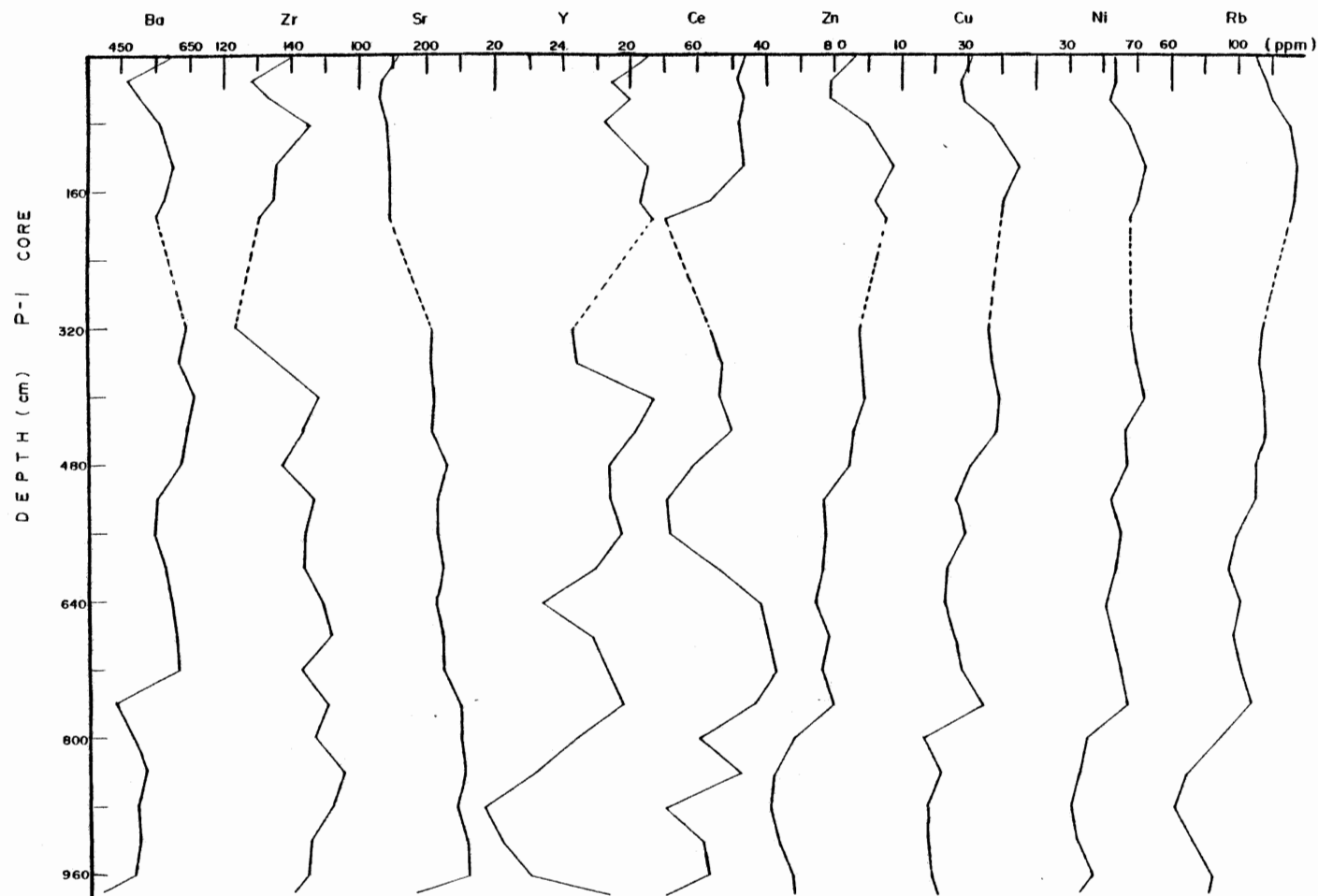


Figure 22. Stratigraphic variations of trace elements versus depth (cm) of core P-1.

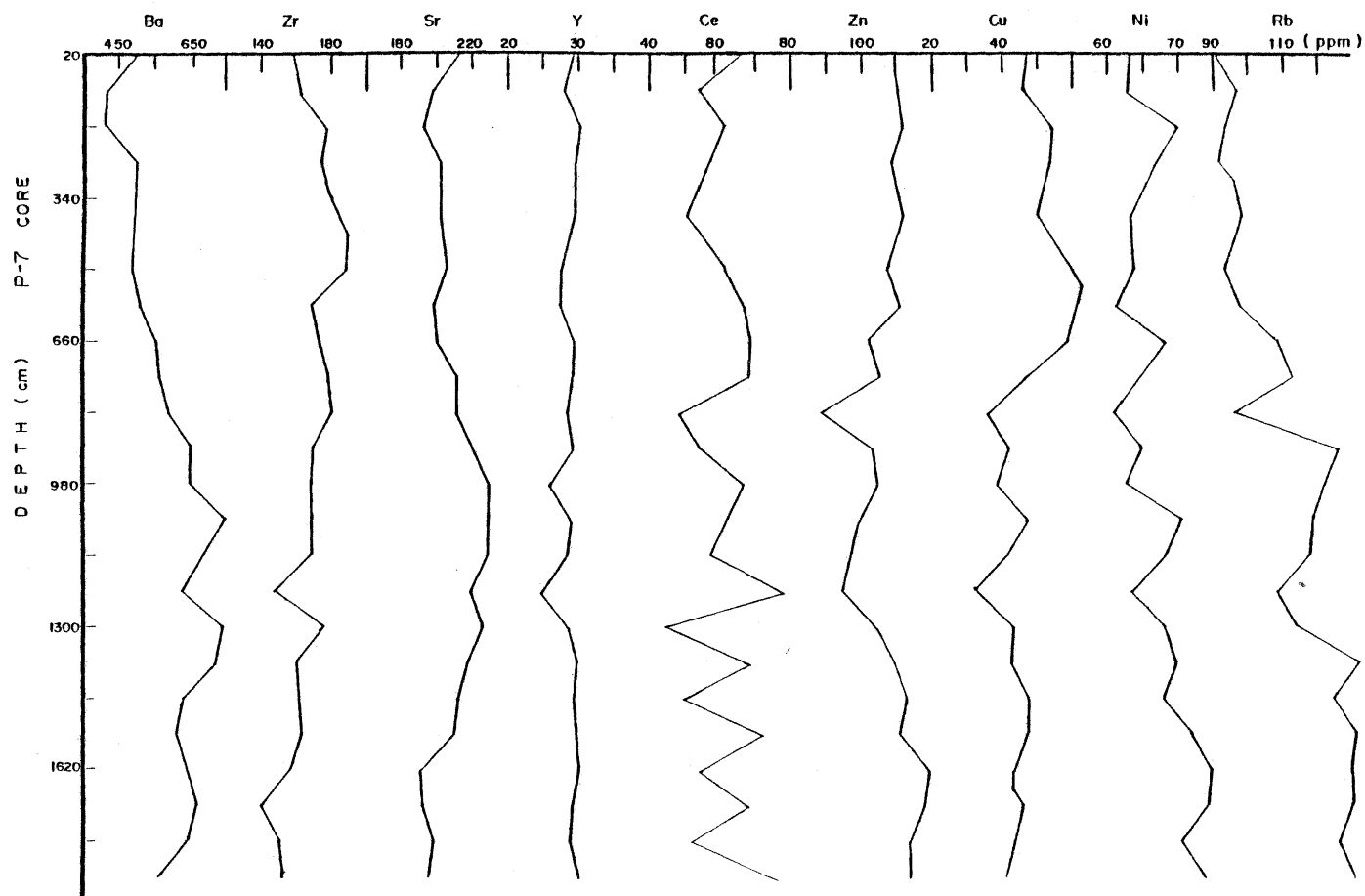


Figure 23. Stratigraphic variations of trace elements versus depth (cm) of core P-7.

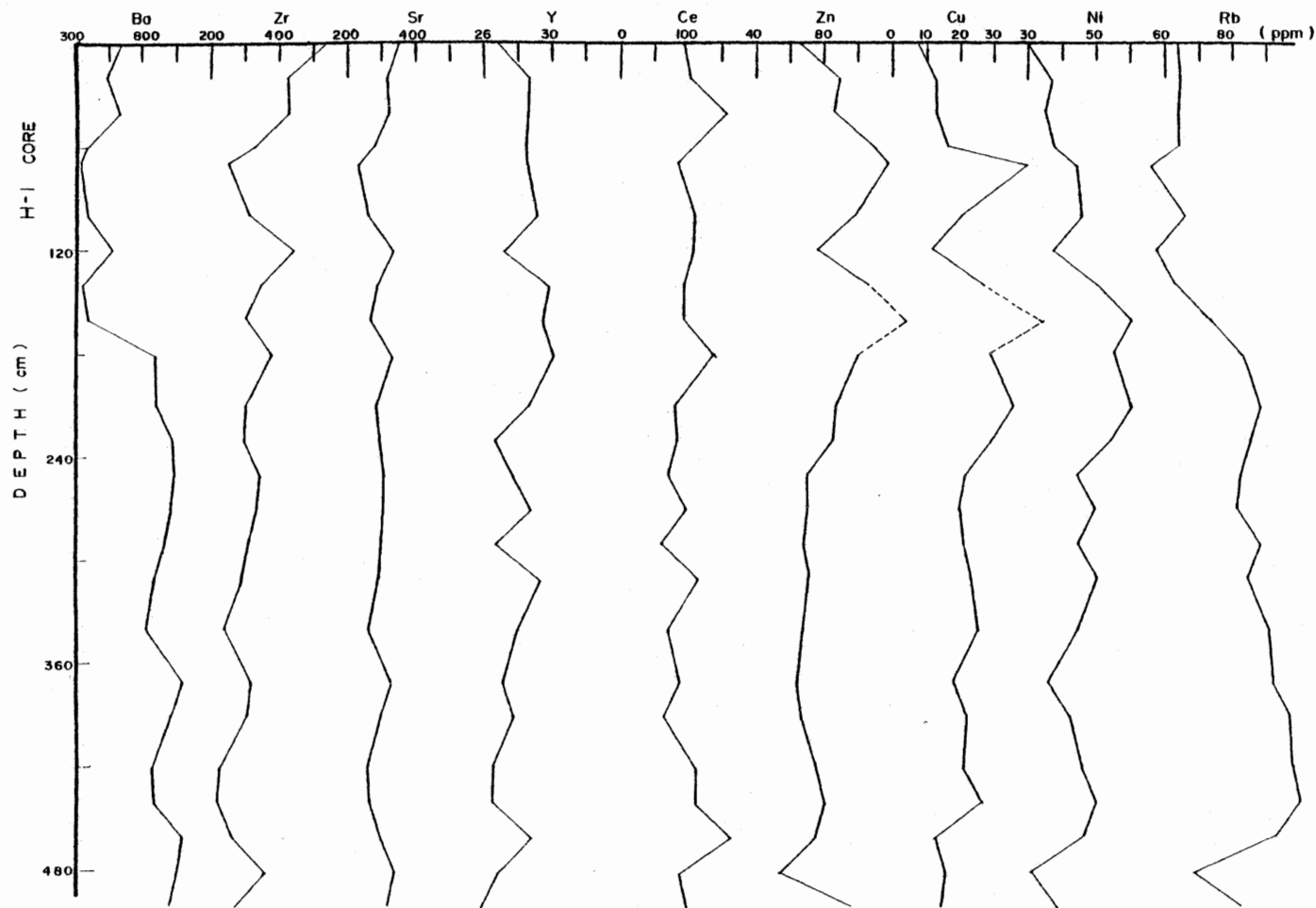


Figure 24. Stratigraphic variations of trace elements versus depth (cm) of core H-1.

analytical precision. Moreover, the high sedimentation rate and small elemental concentration can also produce an irregular profile due to non-uniform deposition of the sediments. The samples which have been analyzed are tabulated in APPENDIX V. During the chemical analysis, six powder-pellet standards (AGV, G-2, GSP, RGM, P-B and SDC) were used for calibrating the background (See APPENDIX III).

### Interpretation of the results

All interpretation of the results in this section was focused on the elements and their relationship with the parent material and surrounding environment. This is because the geochemistry of the trace elements in the Great Lakes Region is closely related to both their origin and anthropogenic loading.

Wedepohl (1969) analyzed the Ba content in igneous rocks and he found that granodiorite and quartz diorite have the highest Ba concentration (about 873ppm) and granite has a lower Ba concentration (about 732ppm). For unconsolidated sediments, clay is usually higher in Ba than silt or sand because of its larger specific surface area. For carbonate rocks, Wedepohl (1969) also found that the average of Ba is about 90ppm. From these results, the Ba concentration is the highest in igneous rocks, and secondly, in shale and sandstone, and with lowest concentration in carbonate rocks.

In this study, the Ba concentration is the highest in H-1 core and the lowest in P-1 core. According to the results proposed by Wedepohl (1969), the result in this study is in agreement with his result and was significantly controlled by both parent material and grain size.

Puchelt (1974) stated that during the weathering processes, Ba could be released preferentially from Ba-bearing orthoclase and mica of igneous rocks, and dissolved into solution. Either increase or decrease in Ba concentration could happen during the weathering processes as shown by several studies. Mainly, the increase or decrease in Ba concentration is affected by climate, the amount of clay minerals and the organic matter content (Wedepohl, 1969; Puchelt, 1974).

Shaw et al. (1967) studied the crystalline rocks of the Canadian Shield and calculated out mean Ba concentration of 1070ppm. Eade and Fahrig (1971) also studied the geochemistry of the Canadian Shield bedrock and found that Ba concentration has a mean value of 1060ppm. Since Harts Lake is located on the Canadian Shield and its highest Ba concentration (an average of 783ppm) among all the cores was more or less influenced by the original Ba concentration in the Canadian Shield bedrock.

The Ba concentration decreases westerly with a similar value in P-1 and P-7 cores is probably affected by the current redistribution and the amount of clay minerals. The increase of Ba in P-7 and H-1 with increasing depth is probably due to

the effect from the bedrock and the organic matter content (Table 9, APPENDIX V).

The Precambrian rocks of the Canadian Shield have a mean value of 400ppm for Zr and 340ppm for Sr (Shaw et al., 1967), although Eade and Fahrig (1971) had a higher Sr concentration with an average of 370ppm. Commonly, Zr is contained in the minerals  $\text{ZrSO}_4$  or  $\text{ZrO}_2$  which have high degree of stability during the weathering process and the decreasing amount with increasing depth is proportional with  $\text{SiO}_2$  and  $\text{TiO}_2$  contents because of same valence +4 (Erlank et al., 1978). Zr concentration for P-1 core seems to increase below 320cm depth. The distribution of Sr in the lake sediments was affected to a certain extent by the presence of Ca because they are all alkaline earth sediments and  $\text{Sr}^{++}$  (ionic radius=1.12Å) is admitted into the smaller  $\text{Ca}^{++}$  (ionic radius=0.99Å) (Wehmiller, 1972).

Wehmiller (1972) stated that the behaviour of Sr in sediments was unpredictable because the deposition occurred in a low temperature environment that could affect Sr concentration. The weathering trend of Sr is probably the same as Ba if  $\text{SO}_4^{=}$  and  $\text{CO}_3^{=}$  were present. From Table 17, Sr and Zr in H-1 core have a high correlation coefficient ( $r=0.87$ ). The reason for this is not fully known. Probably, it is closely related to their concentration in the bedrock. P-1 and P-7 cores do not show good relationship between Zr and Sr ( $r=0.62$  for P-1 and  $r=0.12$  for P-7) (Tables 18 and 19). This is probably due



Table 17. Correlation coefficient matrix for trace elements  
in H-1 core.

	Zr	Sr	Y	S	Cu	Zn	Ni	Rb	Ce
Ba	-0.04	0.15	-0.64	-0.88	-0.71	-0.38	0.06	0.16	-0.36
Zr		0.87	0.04	0.09	-0.39	-0.41	-0.40	-0.01	0.30
Sr			-0.21	-0.09	-0.54	-0.58	-0.60	-0.22	0.21
Y				0.66	0.63	0.51	0.33	-0.28	0.11
S					0.83	0.64	0.07	-0.20	0.22
Cu						0.88	0.50	-0.04	0.02
Zn							0.70	0.05	-0.25
Ni								0.34	-0.39
Rb									0.44
Ce									

Table 18. Correlation coefficient matrix for trace elements  
in P-1 core.

	Zr	Sr	Y	S	Cu	Zn	Ni	Rb	Ce
Ba	0.08	N. D.*	0.08	-0.41	0.28	0.15	0.25	N. D.	0.33
Zr		0.62	-0.31	0.12	-0.54	-0.54	-0.42	0.12	0.59
Sr			-0.63	-0.12	-0.75	-0.68	-0.53	-0.23	0.27
Y				-0.19	0.77	0.81	0.81	0.53	0.23
S					-0.28	-0.32	-0.37	0.04	-0.11
Cu						0.97	0.96	0.44	0.05
Zn							0.96	0.46	0.02
Ni								0.52	0.18
Rb									0.14

\* N. D. = not determined

Table 19. Correlation coefficient matrix for trace elements  
in P-7 core.

	Zr	Sr	Y	S	Cu	Zn	Ni	Rb	Ce
Ba	-0.28	0.61	-0.07	-0.76	-0.32	-0.62	0.32	0.56	-0.25
Zr		0.12	0.29	0.52	-0.32	0.53	-0.33	-0.31	0.03
Sr			-0.04	-0.45	-0.64	-0.48	-0.05	0.37	-0.04
Y				0.02	0.13	0.21	0.33	0.04	-0.05
S					0.14	0.82	-0.53	-0.75	0.13
Cu						0.36	0.29	-0.08	-0.23
Zn							0.28	-0.49	0.03
Ni								0.43	-0.01
Rb									-0.20
Ce									

to the redistribution of the sediment by bottom currents after deposition. The moderate relationship between Sr and Zr for P-1 core is probably affected by its Ca content to a certain extent as discussed above.

Usually, granitic rocks with 60%-70% silicate content have more Y (44ppm) and Ce (85ppm) than basaltic rocks: Y (25ppm) and Ce (66ppm) (Kay, 1972). In alkaline sediments, Y and Ce are higher than in acid sediments with an average of 35ppm of Y and 75ppm of Ce. The sequence for Y in three cores is P-7 (28.5ppm) > H-1 (27.9ppm) > P-1 (26.8ppm) and for Ce is H-1 (93.9ppm) > P-7 (85.1ppm) > P-1 (72.3ppm). Y concentrations in the study areas are lower than the average Y concentrations in granite and higher than that in basaltic rocks and Ce concentrations are almost similar to this. The Ce/Y ratio are H-1 (3.36) > P-7 (2.98) > P-1 (2.69) and these values are all higher than the ratio of 2.50 as calculated by Vinogradov (1959) in their parent rocks.

Herrmann (1974) mentioned that Y and Ce have lower concentrations in carbonate rocks than in shale, and this is in agreement with this study with P-1 the lowest Y and Ce concentrations. Differing from Ce, P-1 core has its Y well related to Cu ( $r=0.77$ ), Zn ( $r=0.81$ ) and Ni ( $r=0.81$ ). H-1 core also has moderate relationship for Y vs. Cu ( $r=0.63$ ) and Y vs. Zn ( $r=0.51$ ). The reason for this is not clearly known.

Zn, Cu and Ni concentrations are all higher in P-1 and P-7 than in H-1. Eade and Fahrig (1971) found that Grenville

Province has an average Ni content of 12ppm, whereas higher Ni (23ppm) and Cu (14ppm) were estimated by Shaw et al. (1967). May and Dreimanis (1973) studied the glacial till in southern Ontario and the average concentration for Zn is 54ppm, Cu is 19ppm and Ni is 24ppm, which are slightly higher than the values calculated out by Shaw et al. (1967) and Eade and Fahrig (1971). Zn, Cu and Ni concentrations in these three cores are sequenced as Zn>Ni>Cu and P-7>P-1>H-1 which are in agreement with the values proposed by May and Dreimanis of Zn (54ppm)>Ni (24ppm)>Cu (19ppm). Smith and More (1972) studied the bottom surface sediments of Upper Lake Michigan and estimated the mean concentrations of Zn, Ni, Cu as 68.4ppm, 40.2ppm and 85.2ppm, respectively. They attributed the high Cu concentration to the controlling effect of drainage from the land and more homogeneous mineralogy of the lake sediments.

The Zn, Ni and Cu concentrations in Georgian Bay are higher than the Zn and Ni concentrations published by Smith and More except Cu. Probably, the concentrations are not only affected by the bedrock material but also by the clay-size fraction and the organic matter content. As the weathering and transportation proceed, the grain size decreases and Zn, Cu and Ni will increase their concentrations by the increasing specific surface area of the sediment grains. The concentrations of these elements in the lake sediments are much higher than those in the bedrock by a factor of 1.65-1.93. According to Tables 17, 18 and 19, P-1 core shows a good correlation of

Zn, Cu and Ni, and P-7 and H-1 cores have fair correlation for Zn, Cu and Ni. The reason for this is not clearly known. The transporting distance of the sediments from the source of their parent material, the depositional environment, the composition of the parent material, the organic matter content and the grain size are all possibilities for P-1 core having good correlation coefficients among Zn, Cu and Ni.

Hutchinson and Fitchko (1974) researched the Great Lakes sediments and stated that Zn element in Georgian Bay has a range from 4.5ppm to 202.5ppm, Cu has a range between 0.8ppm and 61.5 ppm, and Ni has a range 3.0ppm-220ppm. They attributed these concentrations to the results of resuspension, homogenation and redeposition of the lake sediments by current action. They also researched the Ni, Cu and Zn concentrations in outlet sediments around Georgian Bay, with an average of 25.7ppm for Ni, 13.8ppm for Cu and 74.8ppm for Zn. All of the values above are lower than those in the lake sediments studied by Smith and More (1972)(Ni:42.5ppm;Cu:85.2ppm; and Zn:68.4ppm), and the averaged values of P-1, P-7 and H-1 cores. The Ni, Cu and Zn concentrations in the outlet sediments of The Moon River are 19.6ppm, 17.8ppm and 14.7ppm, respectively. The anomaly of Zn here was interpreted by Fitchko and Hutchinson (1975) as "no obvious sources for Zn in the tributaries, so its origin is unknown.". Wedepohl (1969) stated that Zn, Cu and Ni have relatively similar ionic radii  $0.74\text{\AA}$  ( $\text{Zn}^{++}$ ),  $0.69\text{\AA}$  ( $\text{Cu}^{++}$ ) and  $0.72\text{\AA}$  ( $\text{Ni}^{++}$ ), and they can form stable compounds with

organic material. P-1 core has lower concentrations than P-7 core and this is probably due to the distribution of  $\text{PO}_4^{=}$ ,  $\text{S}^{=}$  and  $\text{CO}_3^{=}$  from the Paleozoic carbonate rocks and some terrestrial nutrients (agricultural fertilizers).

If illite was formed from weathered mica or feldspar, Rb concentrations in P-1, P-7 and H-1 cores are related to its  $\text{K}_2\text{O}$  content. Heir and Billings (1972) found that shale has the highest Rb concentration with a mean value of 164ppm, then limestone of 75ppm and dolomite has the lowest value of 45ppm. For the same result in the study areas, the lower Rb concentration in P-1 core is probably influenced by its carbonate content if compared with P-7 core.

Table 20 shows the relationship between the organic matter content and the individual trace element based on the L.O.I. measurement at  $450^\circ\text{C}$  as an equivalent of the organic matter content. Variation in concentrations of Sr, Y, Zn, Cu, Ni and Rb in P-1 core; of Ba, S, Cu and Rb in P-7 core; and of Ba, S and Rb in H-1 core seems closely related to organic matter. It is apparent that H-1 and P-7 could be grouped together to compare with P-1 by the different sediment distribution from the land. Kemp et al. (1976) stated that the relationship between organic matter and trace elements may be indicative of complexing and/or adsorption by organic matter or may be a fortuitous relationship reflecting increased nutrient supply and associated primary productivity in the lakes with time.

Table 20. Correlation coefficients between trace elements and organic matter.

	Ba	Zr	Sr	Y	S	Zn	Cu	Ni	Rb	Ce
P-1	0.321	-0.544	-0.792	0.718	0.302	0.983	0.734	0.720	0.871	0.446
P-7	-0.752	0.447	-0.361	0.283	0.958	0.258	0.704	-0.408	-0.902	0.242
H-1	-0.915	0.350	-0.277	0.410	0.775	0.593	0.198	0.249	-0.658	0.590

Since the relationship between the organic matter content and the clay size fraction is moderate as shown in Table 15, how much the grain size could affect the relationship between organic matter and trace elements is not clearly understood. It seems that Zn, Cu and Ni elements in P-1 core are affected by its small grain size and redistribution of the sediments. The smaller sediment grains could obtain more organic matter and metal ions on the particle surface than the coarser one (Berner, 1971). Thus, P-1 core could have more significant correlation coefficients than P-7 and H-1 by its characteristics.



## Geochemistry of Sulphur

The input of the nutrients has increased significantly in the Great Lakes Region since industrialization was initiated in the surrounding areas. Thus, the change in sulphur concentration could reflect the impact of man's activities on the natural environment. This section is concerned with the extent of the environmental influence.

Berner (1971) reported that sulphur in lake sediments was derived either from organic sulphur compounds or from dissolved  $\text{SO}_4^{=}$  which is closely related to the dissolved oxygen content in lake water. Kemp et al. (1972) studied the Great Lakes sediments and found that sulphides are an important constituent of the deep water reducing muds which have a close relationship to the redox potential and organic matter content. Within a highly oxidizing environment, all the sulphur compounds will be oxidized to sulphate and mixed with original sulphates. If the environment was highly reducing, the anaerobic bacteria will reduce all sulphates to  $\text{H}_2\text{S}$  and  $\text{HS}^-$ , and some natural sulphur together with organic matter will also be degraded (Krauskopf, 1967). This degradation will cause the reduction of  $\text{Fe}^{+3}$  to  $\text{Fe}^{+2}$ , reacting with sulphides to form iron sulphides (pyrite or marcasite). Quantitatively, sulphur in the lake sediments was derived mainly from this process because sufficient microorganisms and decaying organic matter will accelerate the deposition of

sulphides in the sediment (which is much faster than dissolved  $\text{SO}_4^{=}$ ).

Degens (1965) suggested that the concentration of sulphides at the sediment-water interface has a linear relationship with the dissolved  $\text{SO}_4^{=}$  in the overlying water. If there had been a reducing micro-environment within a generally oxidizing environment, the oxidized sediment could contain the same amount of sulphides as in the reduced sediments.

Sulphur concentration in P-1 core is the lowest of the P-1, P-7 and H-1 cores with an average of 1004ppm; H-1 has an intermediate average of 1465ppm and P-7 has the highest average of 1919ppm (See Table 16). The vertical sulphur profile is shown in Figure 25. The sulphur concentration of core P-1 decreases from 1500ppm at the top to 387ppm at 325cm depth and decreases again to 363ppm at 740cm depth. The maximum concentration (1627ppm) occurs at the bottom of the core.

P-7 core shows a relative decrease from the top of the core to about a 9m depth. The maximum concentration (4079ppm) occurs at 595cm depth, whereas the minimum concentration (428ppm) occurs at 1620cm depth. In H-1 core, sulphur concentration reaches the maximum (6643ppm) at 180cm depth, and then decreases to below 250ppm from 220cm downward. The minimum sulphur concentration (76ppm) occurs at the bottom of the core (520cm).

Kemp et al. (1976) reported that sulphur could be considered as a mobile element because it has a high mobility,

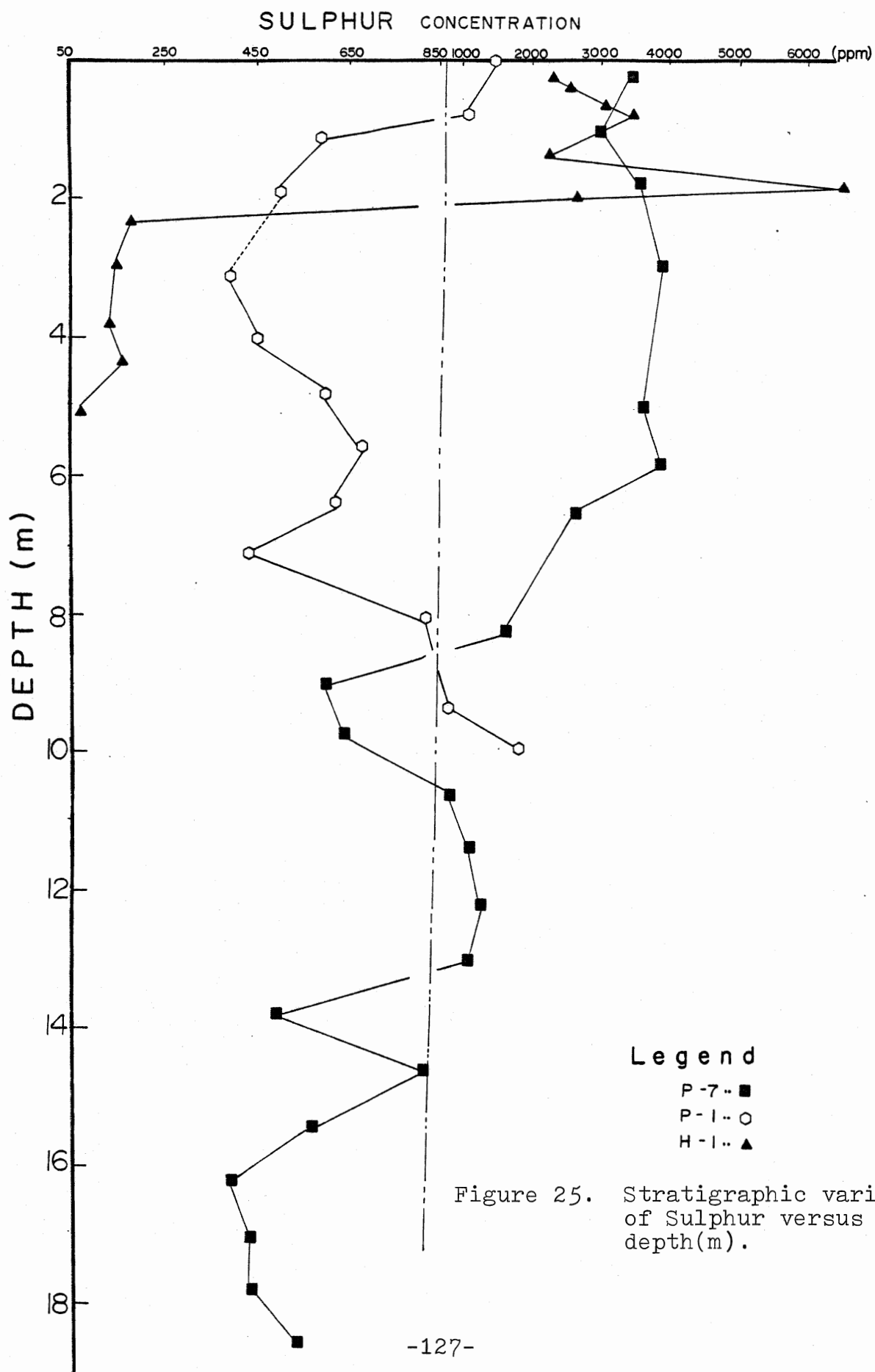


Figure 25. Stratigraphic variations of Sulphur versus depth(m).

being subject to dissolution or migration in the interstitial water, and its high mobility will also influence the sediment chemistry substantially. Kukal (1971) stated that pyrite, marcasite and sulphur will increase with diagenesis, whereas sulphate decreases, which is due to intensive bacterial reduction. Degens (1965) reported that total sulphur has a maximum concentration at the water-sediment interface and the concentration decreases with increasing depth. The decrease of sulphur concentration could be indicated by the decomposition of organic matter in the reducing zone of the sediment stratigraphy.

The concentrations of sulphur in P-1, P-7 and H-1 cores were mainly affected by the following factors: i) composition of the parent material; ii) oxidizing-reducing potential; iii) organic matter content and iv) man's activities. In Table 4, the organic matter content of P-7 core is the highest (7.78%) which is higher than that of H-1 (3.9%) and P-1 (3.09%), and the sulphur concentration has the same trend as organic matter, with  $P-7 > H-1 > P-1$ . The correlation coefficients between sulphur and organic matter content are high for P-7 ( $r=0.958$ ) and H-1 ( $r=0.775$ ) but are low for P-1 ( $r=0.302$ ). The reason why P-1 core has a low correlation coefficient is probably due to the influence by the Paleozoic Cabot Head Formation. Since gypsum and anhydrite are found in the Cabot Head Formation on the Bruce Peninsula (Liberty and Bolton, 1971), the bedrock could release some  $SO_4^{=}$  by simple dissolution, and thus affects the

sulphur concentration in the lake sediments.

For P-7 and H-1 cores on the Canadian Shield, the sulphur concentration was affected by the organic matter because very little pyrite or sulphide occurs in the Precambrian bedrock (Hewitt, 1967). For example, Harts Lake sediment core (H-1) has a sulphur concentration of 6643ppm at 180cm depth and 182ppm at 220cm depth. Since the sediment was derived mainly from the Precambrian Shield bedrock, the sulphur concentration could not be changed so drastically within such a short distance of depth. Furthermore, the sulphur (or sulphide) contribution from the bedrock is steady, and will not change the concentration of the sulphur in the lake sediments so rapidly.

The main factor to affect the sulphur concentration is probably the organic matter content because at 180cm depth, the organic matter content is 11.48%, whereas the organic matter at 220cm depth is only 1.23%. Krauskopf (1967) suggested that sulphide could be formed or increased in a reducing environment with a high organic matter content in spite of its original abundance. Thus, organic matter content in the Georgian Bay sediments is likely to be an important control for sulphur concentration.

Shaw et al. (1967) reported that the range of sulphur concentration in the Precambrian Shield varies from 20ppm to 1000ppm with a mean value of 600ppm. This concentration is less than the average concentrations in three sediment cores.

Commonly, the increase of sulphur concentration after weathering is probably due to the change of Eh (at negative potentials) and pH (at low values). Kemp et al. (1972) stated that the increasing inputs of sulphur by man's activities to the Great Lakes and the increasing loading of the organic sulphur are not clear from the sediment core examination.

As shown in Figure 25, in the top 1m the sulphur concentration of P-1 and P-7 cores increases, whereas sulphur concentration of H-1 core decreases. Since only a few of man's activities were recorded in the drainage basin of Georgian Bay (Fitchko and Hutchinson, 1975; Kemp and Harper, 1977), the increase in sulphur concentration is apparently due to natural eutrophication of the lakes. Thus, the increase in sulphur concentration is again closely related to the organic matter content. The sulphur input from the Sudbury area and the Parry Sound area by industry (i.e. manufacturing of explosives in Parry Sound) is also a possible source (Mirynch, personal comm.).

Table 5 shows that L.O.I. in H-1 core ( $450^{\circ}\text{C}$ ) decreases upward and this is caused by highway reconstruction during the summer, 1973. A sudden input of gravel and sand would increase the ratios of sediment/organic matter substantially in the top part of the sediment because the amount of organic matter by natural input relatively decreases. How much of the sediment was affected by this reconstruction is not known, but the disturbance of the sediment is almost 88cm by direct observation

of sediment colour and sediment stratigraphy. Another factor is probably the input of the detritus of bedrock and the surficial deposits as gravel, pebble and sand, used for construction, which has a low sulphur concentration. For these two reasons, H-1 core has a sulphur concentration that decreases upward.

## DISCUSSION

The study of lake sediments of Georgian Bay, Shepherd Lake and Harts Lake indicates that physical, chemical and sedimentological properties do reflect the characteristics of the depositional environment. Among the controlling factors, bedrock material, organic matter and grain size are the most important that affect the characteristics of the lake sediments. Other less important factors are climate, landscape topography and lake morphometry.

Commonly, the bedrock material from the Canadian Shield influences significantly the  $\text{SiO}_2$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{Ba}$ ,  $\text{Zr}$ ,  $\text{Sr}$ ,  $\text{Y}$ ,  $\text{S}$  and  $\text{Ce}$  contents of the sediments. Harts Lake, and P-7 core in Georgian Bay, have a similar bulk chemical composition as the Shield bedrock except for slight differences in  $\text{SiO}_2$ ,  $\text{CaO}$  and  $\text{Na}_2\text{O}$  values. High  $\text{SiO}_2$  content in the sediment of Harts Lake is probably related to the high diatomite occurrence in the lake basin and surrounding swamps as found by Hewitt (1967). Sediments in Shepherd Lake and P-1 core in Georgian Bay are affected by the Paleozoic carbonate rocks and  $\text{CaO}$  and  $\text{MgO}$  contents are high in lake sediments. P-1 core has higher values in  $\text{CaO}$  (6-7.7%) and in  $\text{MgO}$  (1.1-2.1%) than P-7 core. These higher values are probably caused by the presence of the Paleozoic carbonate strata in its vicinity.

The carbonate carbon (as an equivalent of the difference of loss on ignition at  $450^\circ\text{C}$  and  $1100^\circ\text{C}$ ) in the western part of



Georgian Bay (P-1 core) varies from 3.54% to 15% which is similar to that in eastern Lake Huron where a carbonate content of over 3% (Thomas et al., 1973) was found in the surface bottom sediments. This similarity means that the Paleozoic strata of the Bruce Peninsula could contribute similar amount to both lakes either by shorebluff erosion or fluvial transportation.

The significant correlation between bedrock material and lake sediments is affected by ice movement. On the eastern shore Georgian Bay, till was distributed in rough coincidence with the ice margin. The sediments were derived from the Canadian Shield with little weathering. After the deposition of the sediments, bottom currents redistributed part of them and some sediment input from the western shore of Georgian Bay could have occurred by shorebluff erosion which could increase the carbonate content.

Shepherd Lake sediment has the highest water content and the lowest corresponding bulk density. Although, Perch Lake near Chalk River, Ontario, has many similarities (water depth, sediment type and depositional environment) with Shepherd Lake, the sediment water content in Shepherd Lake is still higher than in Perch Lake because there is no inflow and outflow in Shepherd Lake basin. Generally, if the sediment is composed of organic matter (gyttja), the water content is very high (over 70%) because less compaction was caused by the overlying sediment (low bulk density) and high porosity of the sediment.

Harts Lake sediment has a lower average water content than P-7 core due to the different sediment grain size and sediment composition. The water content in Harts Lake sediment is highly variable from the top to the bottom of the core because it is shallow and small, has insignificant bottom currents and has a high organic matter content near the water-sediment interface.

Although no instrumental method (pycnometer) was used, the data of the bulk density in this study are considered reliable. In Shepherd Lake, the bulk density is slightly higher than  $1.0\text{g/cm}^3$  because of high water content and organic matter content. Some molluscs and plant fragments would change the bulk density significantly by disturbing the sediment homogeneity.

The bulk density of P-7 core is similar to P-10 core except that P-7 core has a narrow range of water content. P-7 has higher values of bulk density than the sediment of Harts Lake due to higher contents of Al and Fe. The pH values in Harts Lake and Shepherd Lake are mainly affected by the bedrock material, the depositional environment, the precipitation and the organic matter content. Because of these, Harts Lake has pH value lower than 7 and Shepherd Lake has pH value higher than 7. All the pH values were lowered near the service road probably due to the result of man's activities (dumping the waste, the waste gas from the vehicles, .... etc.).

The organic matter content is higher in eastern Georgian Bay than in the western part. As both P-1 and P-7 are in the

same depositional basin, P-1 core is far from a vegetational source and little organic matter input comes from the Bruce Peninsula, and P-1 has a lower organic matter average (of 3.09%) than P-7 (of 7.78%). P-7 has higher values than Harts Lake because the relatively deeper water allows for the precipitation of organic matter and more vegetation from Georgian Bay's watershed. Organic matter content in P-7 is similar to that in Lake Superior of 7.5% (Reid, 1961). The organic matter contents from Callender (1969); Kemp et al. (1972) and Thomas et al. (1973) in other Great Lakes' sediments have lower values than the data in this study because they used different procedures for sample preparation, different temperature setting ( $1300^{\circ}\text{C}$ ) for combustion and the methods for calculation.

The grain size decreases along the direction of sediment transport from the Canadian Shield towards the Bruce Peninsula. It is affected by abrasion and progressive sorting during transport. The progressive sorting (selective transportation) is much more important than the abrasion to control the grain size decrease. Generally, in Upper Great Lakes, sediment grain size decreases from Lake Michigan, Lake Superior and Lake Huron towards Georgian Bay. In the study areas, P-1 has smaller grain size than P-7 due to the redistribution and redeposition of sediment by bottom currents.

A good correlation was found between the chemical composition of the lake sediments and their parent material (bedrock

and/or glacial deposits); organic matter and major oxides; organic matter and some trace elements (Ba, S, Zn, Cu and Rb). Because the lake sediments were mainly derived from the Canadian Shield and partly from the Bruce Peninsula, the weathering, transporting and depositional processes are similar for Harts Lake and Georgian Bay (P-7) and different from Shepherd Lake and Georgian Bay (P-1). The good correlation found in this study could reflect the characteristics of the environment for the sediment dispersal, distribution and deposition.

Although the relationship between grain size and geochemistry has not been studied, grain size could influence the geochemistry by changing the specific surface area of the sediment, and thus the correlation between grain size and geochemistry should be significant.

For the climate factor, it was discussed previously that on the east side of Georgian Bay, the temperature is lower and more precipitation was recorded than that on the west side. Thus, more predominant weathering processes could be expected to affect the weathering, erosion, transportation and deposition of the sediments. Besides this factor, landscape topography, water and vegetation cover, and prevailing wind could also affect the behaviour of the lake sediments.

Prest (1961) stated that the soils around Georgian Bay area are mainly derived from Wisconsin glaciation. According to different soil formations and soil types, the origin of the parent

material could be found. From the soil data mentioned previously, the soil types and the soil formations significantly controlled by climate (weathering), particle sizes, degree of sorting, chemical composition of the lake sediments and drainage and landscape topography of the study areas. Moreover, soils that have been derived from the bedrock have identical chemical composition with their parent material (bedrock).

Since specific geochronological data are lacking for the study areas, the deglaciation history could not be easily established. Here, the chemical stratigraphy for major oxides and trace elements, the stratigraphy of the sediment texture, the vertical variation of the grain size and the organic matter content are used as the basis for postulating the deglaciation history in the study areas. Furthermore, Quaternary lake stages (for the lake level), Table 8 from McAtee (1977) (for sediment texture) and the Quaternary Geology written by Prest (1971) (for the distribution of ice covering, the recession of the glacier and the age of the glacial lake stages) are used as supporting evidence for this postulation.

The organic matter content is more sensitive to the environmental changes than the chemical composition of the lake sediments. This is because the lake sediments were influenced by the bedrock for the chemical composition and the organic matter was affected by the vegetation in the watershed and the internal productivity of the lake. When the glacial lake level fell, the

area of exposed land increased considerably and in consequence more organic matter was transported into the lake due to the increased area of vegetation.

During glaciation, the fluctuating glacial lake levels had the following four sequences: i) lowering (Post Algonquin Lake stages); ii) rising (Lake Hough, Lake Stanley-Hough and Lake Stanley-Nipissing); iii) stable (Nipissing Great Lakes I and II) and iv) lowering (Lake Algoma and Georgian Bay). P-1 and P-7 cores were assumed to have been affected by these four sequences, S-1 core was only influenced by Lake Algonquin if the glacial lake phases from Prest (1970) were used. For Harts Lake, the deglaciation history is not clearly known because it has local sedimentation history after Lake Algonquin.

P-7 core could probably have a boundary of Lake Algonquin and Lake Hough at 1220-1280cm depth. The interval from 1220-1280cm to 793cm probably indicates the rising stages of Lake Hough, Lake Hough-Stanley and Lake Stanley-Nipissing. The interval from 793cm to 460-480cm relates to the stable stages of Nipissing Great Lakes I and II because random patterns of organic matter content (either because of natural eutrophication or because of the change of terrestrial plant detritus supply). Afterward, modern Georgian Bay was initiated as indicated by an increasing organic matter content (because the lake level lowered to expose more land).

For geochemical stratigraphy, the major oxides and the trace elements seem to show four zones by different vertical

variation, especially for  $\text{Al}_2\text{O}_3$ ,  $\Sigma\text{FeO}$ ,  $\text{K}_2\text{O}$ ,  $\text{TiO}_2$ , Ba, Zr, S, Ce, Zn, Cu, Ni and Rb (Fig.17 and Fig.23). It also seems that the vertical variation of the trace elements is more sensitive than that of the major oxides affected by the environmental changes.

For the vertical grain size distribution, as mentioned before, there is a major sedimentary break at 1220-1280cm depth (See Fig. 8). This initiation of less fine clay-size sediments is postulated to the low lake level stage -Lake Hough. All the possible postulation for the deglaciation history at P-7 coring site needs more geochronological data for support.

In Shepherd Lake, two  $\text{C}^{14}$  datings have been made:  $6850 \pm 200$  years B.P. (BGS-459) at 570-580cm depth and  $4540 \pm 180$  years B.P. (BGS-458) at 447-457cm depth. In view of the stratigraphic change from mud to gyttja at 825cm and the glacial lake phases from Prest (1970), the lake was isolated from the Main Algonquin stage (11,500 years B.P.) and began its own local sedimentation history. The stratigraphic data concerning major oxides changes ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\Sigma\text{FeO}$ ,  $\text{MgO}$ ,  $\text{CaO}$  and  $\text{TiO}_2$ ) (Fig.19) suggest that the influence of Lake Algonquin ended in Shepherd Lake at 800cm depth. This 25cm of sediment accumulated (800-825cm) was suggested as a "transitory period of isolation".

## SUMMARY AND CONCLUSIONS

From the studies of physical, sedimentological and chemical characteristics of lake sediments covered by this investigation, there is a close relationship between the bedrock, the lake sediments and the sediments' depositional environments. The following conclusions were obtained as a result of this investigation:

- 1) Harts Lake (H-1) and Georgian Bay (P-7) sediments have similar characteristics in respect of water content, bulk density, chemical composition and grain size distribution because the Wisconsin glacier contributed substantial amounts of detritus to these two depositional basins by scouring the Canadian Shield bedrock. The sedimentation process has occurred in a low energy condition as shown by the narrow range of the grain size distribution. Generally, the lake sediments in these two cores are mainly derived from the Canadian Shield.
- 2) The sediments are commonly fine grained and can be classified as fine silt to very fine silty clay. The grain size decreases along the assumed direction of sediment transport from east to west due to abrasion and progressive sorting, and when the grain size decreases, the sorting coefficient decreases and roundness and sphericity increase. Harts Lake has the highest proportion of silt,



probably due to its small size, shallow depth, minor bottom erosion and its proximity to the source of parent material (bedrock and/or glacial deposit). Conversely, sediment of western Georgian Bay has the highest clay content because of relatively great water depth, bathymetrical complexity and the movement of bottom currents.

- 3) With increasing depth, the water content of sediment decreases and bulk density increases. These changes were caused by compaction, the composition of the sediment and the grain size distribution. The measurement of L.O.I. at  $450^{\circ}\text{C}$  could be considered as an equivalent (an indicator of amount) of the organic matter. The highest value at  $450^{\circ}\text{C}$  occurred in Shepherd Lake because of its high gyttja content, and the lowest value occurred in Georgian Bay at the P-1 coring site because of its remoteness from the vegetation sources on the Canadian Shield. The difference of two measurements at two different temperatures is related to the amount of carbonate carbon. Sediments from western Georgian Bay have higher values than those from the Canadian Shield due to the Paleozoic carbonate strata on the Bruce Peninsula. Harts Lake has the lowest difference in loss on ignition values probably because of its identical composition with the Canadian Shield bedrock.
- 4) The high organic matter content in the sediment of

Shepherd Lake reflects its sedimentation history (eutrophication) since the Lake Algonquin stage. Its organic matter (gyttja) is mainly an authigenic product from the decomposition of plants and the remains of insects or animals by the action of micro-organisms.

- 5) The organic matter content shows an enrichment in the surface sediment either by natural eutrophication or by anthropogenic loading. In the study areas, natural eutrophication seems to have more influence on this enrichment than anthropogenic loading if compared to other Great Lakes.
- 6) The pH measurement shows that the composition of the bedrock, the organic matter and the man's activities could affect the pH values of bottom surface sediments significantly. On the Canadian Shield, the sediments are slightly acidic and on the Bruce Peninsula, the sediments are slightly alkaline.
- 7) In contrast to the physical and sedimentological characteristics, the chemical composition of the sediments are different at the two sides of Georgian Bay, and are closely related to their bedrock composition and weathering, as well as to depositional processes.
  - i) With increasing depth,  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\Sigma\text{FeO}$ ,  $\text{TiO}_2$ , Zn, Cu, Ni, and Rb in P-1 core decrease;  $\text{SiO}_2$ , MnO and Cu in P-7 core decrease;  $\text{SiO}_2$ , MnO and Zn in H-1 core decrease;

$\text{SiO}_2$  and  $\text{MnO}$  in S-1 core decrease;  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{Zr}$  and  $\text{Sr}$  in P-1 core decrease;  $\text{Al}_2\text{O}_3$ ,  $\Sigma\text{FeO}$ ,  $\text{MgO}$ ,  $\text{K}_2\text{O}$ ,  $\text{Ba}$ ,  $\text{Ni}$  and  $\text{Rb}$  in P-7 core increase, and  $\text{Al}_2\text{O}_3$ ,  $\Sigma\text{FeO}$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{K}_2\text{O}$  and  $\text{Rb}$  in H-1 core increase.

ii) Lake sediments of Georgian Bay have higher values in  $\text{Al}_2\text{O}_3$ ,  $\Sigma\text{FeO}$ ,  $\text{K}_2\text{O}$ ,  $\text{TiO}_2$ ,  $\text{Zn}$ ,  $\text{Cu}$ ,  $\text{Ni}$  and  $\text{Rb}$ , whereas the lake sediments of Shepherd Lake and Harts Lake have higher trace element concentrations of  $\text{Ba}$ ,  $\text{Zr}$ ,  $\text{Sr}$ ,  $\text{Y}$  and  $\text{Ce}$ .

iii) On the west side of Georgian Bay, lake sediments are characterized by higher  $\text{MgO}$  and  $\text{CaO}$  contents, and P-1 core has low trace element concentrations in respect to  $\text{Ba}$ ,  $\text{Zr}$ ,  $\text{Sr}$ ,  $\text{Y}$ ,  $\text{S}$  and  $\text{Ce}$ .

8) Besides the composition of parental material, the contents of major oxides and the concentrations of trace elements are significantly affected by the organic matter content in the lake sediments.

## RECOMMENDATIONS

The following recommendations for future research are made with respect to the physical, sedimentological and geochemical investigations in this study.

- 1) More data from the surface sediment samples covering the whole of Georgian Bay basin and several neighbouring small lakes (besides Harts Lake and Shepherd Lake) are needed to find the relationship between freshwater lake sediments and the Eh-pH conditions at the water-sediment interface. On the basis of these data, the chemical depositional environment could be established.
- 2) More sediment cores are required from different locations of Georgian Bay in order to have sufficient data for constructing the sedimentary stratigraphy after deglaciation.
- 3) Detailed studies on grain size analysis, from different parts of the lake basins by different methods, are necessary and essential for a better understanding of the sedimentation history.
- 4) The research on the processes of weathering, sediment transport and deposition is required to find out the extent of the chemical and compositional change in

mineralogy of sediments.

- 5) Determination of Ambrosia (ragweed) horizon is recommended as an indicator to reflect the impact of man's activity on sedimentation history since the european settlement.
- 6) Palynological study and geochronological research of the organic remains in the lake basins are required in order to establish a complete sedimentation record and make possible correlation with major oxides, trace elements, as well as the sediment grain-size distribution.

## SELECTED BIBLIOGRAPHY

- Alexandrov, E. A. 1972. Manganese: element and geochemistry. pp. 670-671. In "The Encyclopedia of Geochemistry and Environmental Sciences" (R. W. Fairbridge, Editor). Van Nostrand Reinhold Company, 1321 pp.
- Anderson, T. W. and Terasmae, J. 1966. Palynological study of bottom sediments in Georgian Bay, Lake Huron. Publ. No. 15, Great Lakes Res. Div., the U. of Michigan, pp. 164-168.
- Berner, R. A. 1964. Stability fields of iron minerals in anaerobic sediments. J. Geology, 72, pp. 826-834.
- Berner, R. A. 1971. Principles of chemical sedimentology. McGraw-Hill Book Company, 240 pp.
- Bretz, J. H. 1951. The stages of Lake Chicago, their causes and correlation. Amer. J. Sci., 249, pp. 401-429.
- Brown, D. M., McKay, G. A., and Chapman, L. J. 1974. The climate of Southern Ontario. Climatological Studies No. 5, Environment Canada, Ottawa, 50 pp.
- Buckman, H. O. and Brady, N. C. 1969. The nature and properties of soils. The Macmillan Company, London, 653 pp.
- Callender, E. 1969. Geochemical characteristics of Lake Michigan and Lake Superior sediments. Proc. 12th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res., pp. 124-160.
- Carrol, D. 1958. Role of clay minerals in the transportation of iron. Geochim. Cosmochim. Acta., 14, pp. 1-28.
- Carver, R. E. 1971. Procedures in sedimentary petrology. Wiley-Intersciences, 653 pp.
- Chapman, L. J. and Putnam, D. F. 1966. The physiography of Southern Ontario (2nd Edition). U. of Toronto Press, Toronto, 386 pp.
- Cronan, D. S. and Thomas, R. L. 1970. Ferromanganese concretions in Lake Ontario. Can. J. Earth Sci., 7, pp. 1347-1349.
- Deane, R. E. 1950. Pleistocene geology of the Lake Simcoe District, Ontario. Geol. Surv. Can., Mem. 256, 108 pp.
- Degens, E. T. 1965. Geochemistry of sediments. Prentice-Hall, Inc., Englewood Cliffs, N. J., 342 pp.

- Dell, C. I. 1972. The origin and characteristics of Lake Superior sediments. Proc. 15th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res., pp. 361-370.
- Dell, C. I. 1973a. Vivianite: an authigenic phosphate mineral in Great Lakes sediments. Proc. 16th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res., pp. 1027-1028.
- Dell, C. I. 1973b. A special mechanism for varve formation in a glacial lake. J. Sediment. Petrol., 43, pp. 838-840.
- Doeglas, D. J. 1968. Grain-size indices, classification and environment. Sedimentology, 10, pp. 83-100.
- Dreimanis, A. 1961. Tills of Southern Ontario, In "Soils in Canada" (R. F. Legget, Editor), pp. 80-96.
- Dzwilewski, G. and Richards, J. 1974. Consolidation properties of Wilkinson Basin soils. J. Geotech. Eng. Div. Amer. Soc. Civil. Eng. Proc., 100, No. GT10, pp. 1175-1179.
- Eade, K. E. and Fahrig, W. F. 1971. Geochemical evolutionary trends of continental plates- A preliminary study of the Canadian Shield. Geol. Surv. Can. Bulletin 179, 51 pp.
- Erlank, A. J., Smith, H. S., Marchant, J. W., Cardoso, M. P. and Ahrens, L. H. 1974. Zirconium: In "Handbook of Geochemistry" (K. H. Wedepohl, C. W. Correns, D. M. Shaw, K. K. Turekian and J. Zemann, Eds.). Springer-Verlag, Berlin, 1974.
- Fairbridge, R. W. 1975. The encyclopedia of world regional geology, part I: western hemisphere (Encyclopedia of Earth Science, v. VIII). pp. 193-208.
- Farrand, W. R. 1969. Late-glacial and post glacial sedimentation in the deep basins of Lake Superior, U. S. A., Mitt. Internat. Verein. Limnol., 17, pp. 34-42.
- Fitchko, J. and Hutchinson, T. C. 1975. A comparative study of heavy metal concentrations in river mouth sediments around the Great Lakes. J. Great Lakes Res., 1, pp. 46-78.
- Flanagan, F. J. 1969. U. S. Geological Survey standards- II. First compilation of data for the new U.S.G.S. rocks. Geochim. Cosmochim. Acta, 33, pp. 81-120.
- Flint, R. F. 1971. Glacial and Quaternary geology. John Wiley & Sons, Inc., 892 pp.

- Folk, R. L. 1966. A review of grain size parameters. *Sedimentology*, 6, pp. 73-93.
- Gacs, I. 1975. Distribution of some major and minor elements in the Peach Lake system. pp. 168-188, In "Hydrological Studies on a Small Basin on the Canadian Shield" (P. J. Barry, Edi.). Atomic Energy of Canada Limited, Report AECL-5041/I.
- Gaither, A. 1953. A study of porosity and grain relationship in experimental sands. *J. Sediment. Petrol.*, 23, pp. 180-195.
- Goldich, S. S., Ingamells, L. O. and Thaemlitz, D. 1959. The chemical composition of Minnesota lake marl. Comparison of rapid and conventional chemical methods. *Econ. Geol.*, 54, pp. 285-300.
- Gornitz, V. 1972. Aluminum: element and geochemistry. pp. 21-23. In "The Encyclopedia of Geochemistry and Environmental Sciences" (R. W. Fairbridge, Edi.). Van Nostrand Reinhold Company, 1321 pp.
- Griffiths, J. C. 1967. Scientific method in analysis of sediments. McGraw-Hill Book Company, 508 pp.
- Hare, P. E. 1963. Amino acids in the proteins from aragonite and calcite in the shells of Mytilus Californianus. *Science*, 139, pp. 216-217.
- Harrison, J. E. 1972. Quaternary geology of the North Bay-Mattawa region. *Geol. Surv. Can. Paper* 71-26, 37 pp.
- Harriss, R. C. and Troup, A. G. 1969. Freshwater ferromanganese concretions, chemistry and internal structure. *Science*, 166, pp. 604-606.
- Heier, K. S. and Billings, G. K. 1972. Rubidium. In "Handbook of Geochemistry" (K. H. Wedepohl, C. W. Correns, D. M. Shaw, K. K. Turekian and J. Zemmann, Eds.). Springer-Verlag Berlin, 1972.
- Hesse, P. R. 1971. Soil chemical analysis. Chemical Publishing Co., Inc., 520 pp.
- Herrmann, A. G. 1974. Yttrium and Lanthanides. In "Handbook of Geochemistry" (K. H. Wedepohl, C. W. Correns, D. M. Shaw, K. K. Turekian and J. Zemmann, Eds.). Springer-Verlag Berlin, 1974.



- Hewitt, D. E. 1967. Geology and mineral deposits of the Parry Sound-Huntsville area. O.D.M. Geological Report 52, 65 pp.
- Hough, J. L. 1958. Geology of Great Lakes. Univ. of Illinois Press, Urbana, 313 pp.
- Hough, J. L. 1963. The prehistoric Great Lakes of North America. Amer. Sci., 51, pp. 84-109.
- Hough, J. L. 1966. Correlation of glacial lake stages in the Huron-Erie and Michigan basins. J. Geology, 74, pp. 62-77.
- Hutchinson, T. C. and Fitchko, J. 1974. Heavy metal concentrations and distributions in river mouth sediments around the Great Lakes. Proceedings of the Int'l Conference on Transport of Persistent Chemicals in Aquatic Ecosystems, pp. 69-77.
- Jackson, M. L. R. 1958. Soil chemical analysis. Prentice-Hall, Englewood Cliffs, N. J., 498 pp.
- James, H. L. 1966. Chemistry of the iron-rich sedimentary rocks. U.S.G.S. Prof. Paper 440-W, 61 pp.
- Karrow, P. F., Anderson, T. W., Clarke, A. H., Delorme, L. D. and Sreenivasa, M. R. 1975. Stratigraphy and age of Lake Algonquin sediments in south-western Ontario, Canada. Quat. Res., 5, pp. 49-87.
- Kay, R. 1972. Cerium: element and geochemistry. pp.145-146. In "The Encyclopedia of Geochemistry and Environmental Sciences" (R. W. Fairbridge, Edi.). Van Nostrand Reinhold Company, 1321 pp.
- Kay, R. 1972. Yttrium: element and geochemistry. pp. 1291-1292. In "The Encyclopedia of Geochemistry and Environmental Sciences" (R. W. Fairbridge, Edi.). Van Nostrand Reinhold Company, 1321 pp.
- Kemp, A. L. W. 1969. Organic matter in the sediments of Lakes Ontario and Erie. Proc. 12th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res., pp.237-249.
- Kemp, A. L. W., Anderson, T. W., Thomas, R. L. and Mudrochova, A. 1974. Sedimentation rates and recent sediment history of Lakes Ontario, Erie, and Huron. J. Sediment. Petrol., 44, pp. 207-218.

- Kemp, A. L. W., Gray, C. B. J., and Mudrochova, A. 1972. Changes in C,N,P and S in the last 140 years in three cores from Lakes Ontario, Erie and Huron. In "Nutrient in Natural Waters" (H. E. Allen & J. R. Kramer, Eds.). John Willey and Sons, N. Y., pp. 251-279.
- Kemp, A. L. W. and Harper, N. S. 1977. Sedimentation rates in Lake Huron and Georgian Bay. J. Great Lakes Res., Internat. Assoc. Great Lakes Res., 3, pp. 215-220.
- Kemp, A. L. W. and Lewis, C. F. M. 1968. A preliminary investigation of chlorophyll degradation products in the sediments of Lake Erie and Lake Ontario. Proc. 11th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res., pp. 206-229.
- Kemp, A. L. W. and Thomas, R. L. 1976. Cultural impact on the geochemistry of the sediments of Lakes Ontario, Erie and Huron. Geoscience Canada, 3, pp. 191-207.
- Kemp, A. L. W., Thomas, R. L., Dell, C. I., and Jaquet, J. M. 1976. Cultural impact on the geochemistry of sediments in Lake Erie. J. Fish. Res. Board Canada, 33, pp. 440-462.
- Koldijk, W. S. 1968. On environment-sensitive grain-size parameters. Sedimentology, 10, pp. 57-69.
- Kominz, M., Heath, G. R., and Moore, T. C. 1977. Bulk density of pelagic sediments from the Equatorial Pacific estimated from carbonate content, age and subbottom depth. J. Sediment. Petrol., 47, pp. 1593-1597.
- Krauskopf, K. B. 1967. Introduction to geochemistry. McGraw-Hill Book Company, 721 pp.
- Krumbein, W. C. and Pettijohn, F. J. 1938. Manual of sedimentary petrography. Appleton Century Company, Inc., New York, 549 pp.
- Krumbein, W. C. and Sloss, L. L. 1963. Stratigraphy and sedimentation. 2nd Edition, W.H. Freeman & Company, 660 pp.
- Kukal, Z. 1971. Geology of recent sediments. Academic Press, Prague, 490 pp.
- Lee, H. A., Craig, B. G. and Fyles, J. G. 1957. Keewatin ice divide. Geol. Surv. Amer. (Abs.), pp. 1760-1761.
- Levinson, A. A. 1974. Introduction to exploration geochemistry. Calgary, Applied Publishing Ltd., 612 pp.

- Lewis, C. F. M. 1969. Late Quaternary history of lake levels in the Huron and Erie basins. Proc. 12th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res., pp. 250-270.
- Lewis, C. F. M., Anderson, T. W. and Berti, A. A. 1966. Geological and palynological studies of early Lake Erie deposits. Proc. 9th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res., pp. 176-191.
- Liberty, B. A. 1955. Stratigraphic studies of the Ordovician system in Ontario. Proc. Geol. Assoc. Can., 7, pp. 139-147.
- Liberty, B. A. and Bolton, T. E. 1971. Paleozoic geology of the Bruce Peninsula area, Ontario. Geol. Surv. Can. Memoir 360, 163 pp.
- May, R. W. and Dreimanis, A. 1973. Differentiation of glacial tills in Southern Ontario, Canada, based on their Cu, Zn, Cr and Ni geochemistry. In "The Wisconsinian Stage" (R. F. Black, R. P. Goldthwait, and H. B. Willman, Eds.), Geol. Surv. Amer. Memoir 136, pp. 221-228.
- McAtee, C. L. 1977. Palynology of late-glacial and postglacial sediments in Georgian Bay, Ontario, Canada, as related to the Great Lakes history. M.Sc. thesis, Dept. of Geological Sciences, Brock University, 153 pp.
- McKeague, J. A. 1976. Manual on soil sampling and methods of analysis. Agriculture Canada, Research Branch, Soil Research Institute, Ottawa, 133 pp.
- Meade, R. H. 1966. Factors influencing the early stages of the compaction of clays and sands - review. J. Sediment. Petrol., 36, pp. 1085-1101.
- Meteorological Branch. Canada Year Book 1959-1960. The climate of Canada. (A. Thomson, Edi.), 74 pp.
- Mott, R. J. 1966. Quaternary palynological sampling techniques of the Geological Survey of Canada. Geol. Surv. Can. Paper 66-41, 24 pp.
- Nissenbaum, A. and Swaine, D. J. 1976. Organic matter-metal interaction in Recent Sediments: the role of humic substances. Geochim. Cosmochim. Acta, 40, pp. 809-816.
- Nockolds, S. R. 1954. Average chemical composition of some igneous rocks. Bull. Geol. Soc. Amer., 65, pp. 1007-1032.

- Norrish, K. and Hutton, J. T. 1969. An accurate X-ray spectrographic method for the analysis of a wide range of geological samples. *Geochim. Cosmochim. Acta*, 33, pp. 431-453.
- Peach, P. A. and Perrie, L. A. 1975. Grain size distribution within glacial varves. *Geology*, pp. 43-46.
- Perrie, L. A. and Peach, P. A. 1973. Gelatin coated microscope slides in sedimentary size analysis. *J. Sediment. Petrol.*, 43, pp. 1174-1175.
- Pettijohn, F. J. 1963. Chemical composition of sandstone-excluding carbonate and volcanic sands, U.S.G.S. Prof. Paper 440-S, 19 pp.
- Pettijohn, F. J. 1975. *Sedimentary rocks*. Harper & Row Publisher, 628 pp.
- Phillips, D. W. and McCulloch, J. A. W. 1972. The climate of the Great Lakes Basin. *Climatological Studies No. 20*, Environment Canada, Information Canada, Ottawa, 40 pp.
- Pilkey, O. H. 1972. Calcium: element and geochemistry. pp. 100-103, In "The Encyclopedia of Geochemistry and Environmental Sciences" (R. W. Fairbridge, Edi.). Van Nostrand Reinhold Company, 1321 pp.
- Prest, V. K. 1961. Geology of the soils of Canada. pp. 6-21. In "Soils in Canada" (R. F. Legget, Edi.). U. of Toronto Press, 240 pp.
- Prest, V. K. 1970. Quaternary geology of Canada. pp. 675-764. In "Geol. Surv. Can. Econ. Geol. Report No. 1" (R. J. W. Douglas, Edi.).
- Puchelt, H. 1974. Barium. In "Handbook of Geochemistry" (K. H. Wedepohl, C. W. Correns, D. M. Shaw, K. K. Turekian and J. Zemann, Eds.). Springer-Verlag Berlin, pp. 56-A-1-56-0-2, 1974.
- Putnam, D. F. 1952. *Canadian Regions*. J. M. Dent & Sons (Canada) Ltd., 601 pp.
- Reid, J. R. 1961. Investigation of bottom cores from north and south-central Lake Superior. *Proc. 7th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res.*, pp. 126-144.
- Reineck, H. E. and Singh, I. B. 1975. *Depositional sedimentary environments*. Springer-Verlag Berlin, 439 pp.

- Richards, N. R. 1961. The soils of Southern Ontario. pp. 174-182. In "Soils in Canada" (R. F. Legget, Edi.), 240 pp.
- Rossmann, R. and Seibel, E. 1977. Surficial sediments redistribution by wave energy: element-grain size relationships. J. Great Lakes Res., 3, pp. 258-262.
- Rowe, J. S. 1972. Forest regions of Canada. Dept. of Environ., Canada Forestry Surv., Publ. 1300, 172 pp.
- Sarmiento, R. and Kirby, R. A. 1962. Recent Sediments of Lake Maracaibo. J. Sediment. Petrol., 32, pp. 698-724.
- Schoettl, M. and Friedman, G. M. 1973. Organic carbon in sediments of Lake George, New York. Bull. Geol. Soc. Amer., 84, pp. 191-197.
- Schubel, J. R. 1969. Size distribution of the suspended particles of the Chesapeake Bay turbidity maximum. Netherlands J. of sea Research, 4, pp. 283-309.
- Shaw, D. M., Reilly, G. A., Muysson, J. R., Pattenden, G. E. and Campbell, F. E. 1967. An estimate of the chemical composition of the Canadian Precambrian Shield. Can. J. Earth Sci., 4, pp. 829-853.
- Short, N. M. 1961. Geochemical variations in four residual soils. J. Geol., 69, pp. 534-571.
- Siever, R. 1962. Silica solubility, 0 -200 C, at the diagenesis of siliceous sediments. J. Geol., 70, pp. 127-150.
- Slatt, R. M. 1975. Dispersal and geochemistry of surface sediments in Halls Bay, North-Central Newfoundland: application to mineral exploration. Can. J. Earth Sci., 12, pp. 1346-1361.
- Sly, P. G. 1969. Sedimentological studies in the Niagara area of Lake Ontario, and in the area immediately north of the Bruce Peninsula in Georgian Bay. Proc. 12th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res., pp. 341-346.
- Sly, P. G. and Lewis, C. F. M. 1972. The Great Lakes of Canada-Quaternary geology and limnology. Excursion A43, XXIV International Geological Congress, 92 pp.
- Sly, P. G. and Thomas, R. L. 1974. Review of geological research as it relates to an understanding of Great Lakes limnology. J. Fish. Res. Board Can., 31, pp. 795-825.

- Smith, P. A. and Moore, J. R. 1972. The distribution of trace metals in the surficial sediments surrounding Keweenaw Point, Upper Michigan. Proc. 15th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res., pp. 383-393.
- Solohub, J. T. and Llovan, J. E. 1970. Evaluation of grain-size parameter in lacustrine environments. J. Sediment. Petrol., 40, pp. 81-101.
- Somers, L. H. and Josephson, P. O. 1968. Bottom sediments of Southwestern Lake Michigan. Proc. 11th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res., pp. 245-252.
- Spencer, D. W. 1963. The interpretation of grain-size distribution curves of clastic sediments. J. Sediment. Petrol., 33, pp. 180-190.
- Swift, D. J. F., Schubel, J. R. and Sheldon, R. W. 1972. Size analysis of fine-grained suspended sediments: a review. J. Sediment. Petrol., 42, pp. 122-134.
- Terasmae, J., Karrow, P. F. and Dreimanis, A. 1972. Quaternary stratigraphy and geomorphology of the eastern Great Lakes region of Southern Ontario. Excursion A42, XXIV International Geological Congress, 75 pp.
- Thomas, R. L. 1969a. A note on the relationship of grain size, clay content, quartz and organic carbon in some Lake Erie and Lake Ontario sediments. J. Sediment. Petrol., 39, pp. 803-809.
- Thomas, R. L. 1969b. The qualitative distribution of feldspar in surficial bottom sediments from Lake Ontario. Proc. 12th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res., pp. 364-379.
- Thomas, R. L., Kemp, A. L. W. and Lewis, C. F. M. 1972. Distribution of composition and characteristics of the surficial sediments of Lake Ontario. J. Sediment. Petrol., 42, pp. 66-84.
- Thomas, R. L., Kemp, A. L. W. and Lewis, C. F. M. 1973. The surficial sediments of Lake Huron. Can. J. Earth Sci., 10, pp. 226-271.
- Thomas, R. L., Jaquet, J. M. and Kemp, A. L. W. 1976. Surficial sediments of Lake Erie. J. Fish. Res. Board Can., 33, pp. 385-403.

- Uzdowski, H. E. 1974. Magnesium. In "Handbook of Geochemistry" (K. H. Wedepohl, C. W. Correns, D. M. Shaw, K. K. Turekian and J. Zemann, Des.). Springer-Verlag Berlin, 1974.
- Vinogradov, A. P. 1959. The geochemistry of rare and dispersed chemical elements in soils. (2nd edition, translated from Russian), Consultants Bureau, New York, 209 pp.
- Visher, G. S. 1969. Grain-size distribution and depositional processes. J. Sediment. Petrol., 39, pp. 1074-1106.
- Wakatsuki, T., Furukawa, H. and Kyuma, K. 1977. Geochemical study of the redistribution of elements in soil- I. Evaluation of degree of weathering of transported soil materials by distribution of major elements among the particle size fractions and soil extract. Geochim. Cosmochim. Acta, 41, pp. 891-902.
- Webber, L. R. 1976. Ontario soils (K. M. King, Edi.). Ministry of Agriculture and Food, Publ. 492, 54 pp.
- Wedepohl, K. H. 1969. Composition and abundance of common igneous rocks. pp. 227-249. In "Handbook of Geochemistry" (K. H. Wedepohl, C. W. Correns, D. M. Shaw, K. K. Turekian and J. Zemann, Eds.). Springer-Verlag Berlin, 1969.
- Wehmiller, J. 1972. Strontium: element and geochemistry and strontium cycle. pp. 1121-1123. In "The Encyclopedia of Geochemistry and Environmental Sciences" (R. W. Fairbridge, Edi.). Van Nostrand Reinhold Company, 1321 pp.
- Wetzel, R. G. 1975. Limnology. W. B. Saunders Company, Philadelphia, 743 pp.
- Williams, J. D. H., Syers, J. K., Shukia, S. S., Harris, R. F. and Armstrong, D. E. 1971. Levels of inorganic and total phosphorus in lake sediments as related to other sediment parameters. Environmental Science & Technology, 5, pp. 1113-1120.
- Yaalon, D. H., Brenner, I. and Koyumdjisky, H. 1974. Weathering and mobility sequence of minor elements on a basaltic pedomorphic surface, Galilee, Israel. Geoderma, 12, pp. 233-244.
- Yokoyama, T., Horie, S., Fuji, N., Handa, N., Kanari, S., Yamamoto, A. and Yasokawa, K. 1975. Comments on columns of the 200M- long core sediments from Lake Biwa and mutual relation of the samples used for various analyses. pp. 81-93. In "Paleolimnology of Lake Biwa and the Japanese Pleistocene" (S. Horie, Edi.), 3, 577 pp.

## APPENDIX I

### Sediment Sampling in Georgian Bay

The surface bottom sediment samples were collected at the intersections of a 10Km grid, based on the Universal Transverse Mercator (UTM) coordinate system, by Shipek bucket sampler which recovers the sediments undisturbed and permits subsampling of the sediment surface immediately on retrieval (Kemp and Lewis, 1968).

The piston cores (P-1 and P-7) were collected with a 545Kg Alpine Piston corer. The acetate tubes (outer diameter=6.4cm; inner diameter=5.7cm) that contained the sediment recovered, were removed from the steel pipe of the corer and examined externally to ensure that the quality of the cores was suitable for laboratory examinations (Kemp, 1969). Both cores were cut into 80cm sections, capped, labelled, wrapped in Saran Wrap, stored in cardboard boxes, and transported back to CCIW for future logging and various analyses (CCIW Cruise Report 73-05-002, 1973).

### Sediment Sampling in Shepherd Lake and Harts Lake

In Shepherd Lake, the lake surface was approximately divided into quadrants by N-S and E-W lines intersecting at the



lake centre, and one surface sediment sample was collected from nearly the centre of each quadrant. For the surface sediment sampling, simple insertion of an acetate tube into the sediment was used because of the lake's shallow depth. In Harts Lake, seven surface sediment samples were obtained. Two of them (#4 and #7) were collected at the river mouth (northwest part) and swamp area (southeast part), respectively. The remaining five samples were obtained by GSC gravity corer (3.2cm in diameter and 122cm in length)(Mott,1966) at the lake periphery with similar water depth. All the samples were placed in plastic bottles which were capped tightly.

The coring site in Shepherd Lake was chosen near the lake centre and in Harts Lake, the coring site was in the deepest part of the lake. Coring was carried out with Brown sampler (for water-sediment interface sampling) and Livingstone sampler (for coring more compact sediments at greater depth). Usually, this coring procedure (Mott,1966) can provide a sediment without any gaps in the sedimentary stratigraphy. The Brown sampling method allowed visual inspection of the sediment after coring because of transparent plastic tube (this 5cm in diameter and 180cm in length core was thus called "Brown core") and examination is possible for actual length, sediment type, colour, etc., but the sediment in the metal Livingstone coring tube (this 3.8cm in diameter and 100cm in length coring tube was called "Livingstone core") was simply recorded in respect to recovery length.

All the cores (tubes) were capped, labelled, stored in the core boxes, and transported back to Brock University for storage and future study.

## APPENDIX II

### Stratigraphic Description of Georgian Bay Core P-7

Depth (Cm)	Sediment Characteristics
0-40	Silt to silty clay, dark olive grey (5Y 3/2), non-calcareous, soft
40-46	Silty clay, light olive grey (5Y 5/2), non-calcareous, soft, H <sub>2</sub> S odour
46-91	Clayey silt mud, olive grey, sticky, stiff, colour and texture are uniform. 44-67.5cm; some marl or calcareous fragments
91-170	Clayey silt, colour intermixed with (5Y 5/2) and (5Y 3/2), non-calcareous, non-laminated, sickly, stiff
170-234	Silty clay, light olive grey (5Y 5/2) and moderate olive brown (5Y 4/4), some moderate brown (5YR 4/4) laminations with mica, firm, sticky, H <sub>2</sub> S odour
234-321	Silty clay; 234-280 olive grey 280-307 light olive brown (5Y 5/6), intermixed with olive grey (5Y 3/2) 307-321 olive grey
321-402	Silty clay, dark grey (5Y 4/1), non-calcareous, non-laminated, sticky
402-429	Silty clay, dark grey, some vivianite (Fe <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> ·8H <sub>2</sub> O) clusters, non-calcareous, stiff
429-502	Silty clay, dark olive grey, uniform texture, stiff
502-591	Silty clay, light olive brown (5Y 5/6), lamination (507.7-507.8cm), stiff, sticky, vivianite clusters, H <sub>2</sub> S odour

- 591-660 Silt, olive grey to light olive grey, non-calcareous, H<sub>2</sub>S odour 622-622.5cm; laminations with light olive brown (5Y 5/6), vivianite clusters 599-601cm; large pebbles (0.3-0.5cm in diameter) in light brown colour
- 660-793 Silty clay, dark grey (5Y 4/1) to olive grey, H<sub>2</sub>S odour
- 793-849 Silt to silty clay, non-calcareous, laminated 793-796cm; moderate olive brown to light olive grey, some micaceous minerals 812-814cm, 826-827cm; light olive brown, very fine wood fragments
- 849-921 Very fine clay, olive grey to dark olive grey, uniform texture, stiff
- 921-1104 Fine silty clay, dark olive grey, non-calcareous, uniform texture, very strong H<sub>2</sub>S odour, tree fragments, vivianite at 1077cm
- 1104-1120 Fine silty clay, laminated with light olive brown (5Y 5/6) and light olive grey (5Y 5/2), uniform texture
- 1120-1283 Silty clay, dark yellow (5Y 6/4), non-calcareous, non-laminated, sticky, soft 1209-1249cm; dark brown
- 1283-1291 Silty clay, greyish olive (10Y 4/2) with four dusky yellow bands, sticky, stiff
- 1291-1407 Fine silty clay, olive grey, firm, sticky, H<sub>2</sub>S odour 1385.5-1385.7cm; dark brown laminations
- 1407-1487 Fine clay, olive grey (5Y 3/2), uniform texture, sticky, stiff 1421.5-1450.2cm; laminations in light brown (5YR 5/6)
- 1487- 1858 Very fine clay, light olive grey, non-calcareous, non-laminated, sticky, stiff

# Stratigraphic Description of Harts Lake (H-1) Sediment Core

Depth (Cm)	Sediment Characteristics
0-27	Coarse silt, yellowish brown, high content of wood fragments, pebbles (0.4-0.8cm in diameter)
27-88	Fine silt to coarse silt, non-laminated, high organic content 50-80cm; dark grey 80-82cm; some clays 82-87cm; grey outside, dark grey inside
88-183	Coarse silt, dark grey, non-laminated, sticky, stiff, wood fragments 98-125cm; dark grey to grey, very compact 125-182cm; silt content higher, organic matter lower
183-280	Coarse silt, grey, intermixed with very fine sand (275-280cm)
280-331	Clay, dark brown, non-calcareous, non-laminated, uniform texture, stiff, firm
331-335	Coarse silt to silty clay, light grey colour, non-calcareous, non-laminated
335-392	Silt, light brown to greyish brown, pebbles (at 392cm) in red and dark brown
392-500	Clay, dark grey, dark brown and brown, non-calcareous, sticky, stiff
500-530	Very fine clayey sand to very coarse clayey silt, light grey to dark brown, uniform texture, non-sticky, more stiff, pebbles (at 514cm) in dark brown colour

## Stratigraphic Description of Shepherd Lake (S-1) Sediment Core

Depth (Cm)	Sediment Characteristics
0-145	Pure gyttja, dark green to light black, watery, rubbery, soft, plant fragments, no sand and mud or very little mud
145-330	Fine algal gyttja, dark green with greyish tint, occasional seeds and plant fragments, molluscs (320cm depth, pelecypods and gastropods)
330-517	Gyttja, dark grey, uniform texture, soft 340-346cm; molluscs 392-410cm; abundant molluscs 442-451cm, 458-470cm; wood fragments 500-502cm; light brown colour in a band with leaves
517-708	Algal gyttja, dark green to greyish, occasional seeds, plant fragments and variation of subtle colour abundant molluscs (557-576cm) but decreasing from 613cm downward
708-825	Gyttja with very fine mud, dark green, few seeds and molluscs, twig about 2.1cm long (724cm in depth)
825-878	Clay intermixed with very fine sand to coarse silt, grey to dark grey, laminated, not uniform of texture, stiff (846-852cm, 856-858cm, 867-868cm and 876-878cm, laminations of clay layers)

## APPENDIX III

### Physical Analysis

The length of subsampled core segments was measured and they were weighed immediately on a Mettler H10 balance ( $d=0.1\text{mg}$ ) before drying. After this step, all samples were placed into pre-weighed, pre-marked beakers, and dried in single-wall Blue M oven at  $110^{\circ}\text{C}$  for 24-30 hours. The subsample length of 5cm is essential to obtain sufficient weight and amount of sediment for quantitative measurements. After drying, the dry weight of samples was determined. The water content and the bulk density of sediment samples can be expressed by the following equations:

Water Content (%) =  $\frac{\text{Original wet weight} - \text{Final dried weight}}{\text{Original wet weight}} \times 100$

$$\text{Bulk Density (g/cm)} = \frac{\text{Original wet weight}}{L \times \pi \times r^2}$$

in which L: the length of the sample (core segments in cm)

r: the radius of the sample (equal inside radius of the core tube in cm)

If the sediment was predominantly composed of till, sieving of smaller than 2mm fraction was necessary to eliminate the gravel (granule and pebble). After weighing, the samples were powdered by mortar and pestle to pass through a 100-mesh sieve.  $1 \pm 0.0000$  gram of each sample was placed in a pre-weighed porcelain crucible and the samples were then ashed in a Thermolyne furnace at a temperature  $450^{\circ}\text{C}$  for 12-16 hours. After ashing, they were

placed in a desiccator and cooled down to room temperature. The sample weights were recorded and the samples were reheated in the same furnace at 1100°C for at least 30 minutes. Samples were weighed again and the Loss on Ignition (L.O.I.) at two different temperatures was expressed by the following equation:

$$\text{Loss on Ignition} = \frac{\text{Original weight} - \text{Final weight}}{\text{Original weight}} \times 100$$

Due to the small amounts of sample analyzed for L.O.I. measurement, the inaccuracy (percent error) is about  $\pm 10\%$  to  $\pm 15\%$ . For S-1 core, it was more inaccurate because the ignition occurred mostly at 450°C, and combusted the organic matter (gyttja).

#### Chemical Analysis

The chemical analysis included pH measurement, determination of ten major oxides ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\Sigma\text{FeO}$ ,  $\text{CaO}$ ,  $\text{MgO}$ ,  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$ ,  $\text{TiO}_2$ ,  $\text{MnO}$  and  $\text{P}_2\text{O}_5$ ) and ten trace elements (Ba, Zr, Sr, Y, S, Zn, Cu, Ni, Rb and Ce). On ten surface samples from Harts Lake and Shepherd Lake, pH value was measured directly with a I.B.C. pH meter. At the beginning, a plastic bottle of temperature controlled pH=7.4 buffer was equilibrated with the lake surface samples for 15 minutes. Afterwards, the pH meter was adjusted to the samples' temperature synchronously and a pH=6.9 buffer was used for additional calibration of the pH meter. The sample composed of water and sediment was then stirred evenly so that the measurements could be made by directly immersing the glass electrode



in this aqueous mixture of sediment sample. The pH measurement for the core sediment was not carried out because the sediment has been stored in the cold room for a period of time without extrusion and logging. The pH measurements would not be very significant if the storing time has been more than a few weeks.

Because of the prerequisite of passing samples through a 325-mesh sieve, 16 grams of oven-dried sediment was weighed and ground in a "Pulverit Model 502" ball mill for 15-20 minutes.  $1.0000 \pm 0.0000$  gram of powdered sample and 10 grams of flux (Lithium Tetraborate) were weighed separately, and another weighed amount of flux equivalent to L.O.I. at  $1100^{\circ}\text{C}$  was added to mix them. For example, if the L.O.I. value was 13.89%, then additional flux needed is 0.1389g. The powder was poured into a platinum crucible and inserted into furnace at  $1100^{\circ}\text{C}$  for exactly the same time used for L.O.I. measurements. The purpose of this procedure was to compensate sediment loss during the ignition. Due to flux characteristics, the mixture was then melted homogeneously by stirring and swirling the crucible during the ignition period. Meanwhile, a platinum disc mould was heated on a propane burner. After the sample was fused and mixed, it was poured into the heating mould directly. The burner was turned off and the mould was allowed to cool to room temperature. Because the difference between the two material's (mould and the sample) contractive coefficient, the disc sample can be removed from the mould easily.

To obtain a sufficient amount of sample for trace element analysis, 15 grams of powdered sediment were weighed, mixed constantly with 4 X-ray mix tablets in a mortar with a pestle, then decanted into an aluminum mould and pressed under 20-25 Kg/cm<sup>2</sup> by a Herzog Oleo-Hydraulic hand press for at least 10 seconds. The mould were marked and the samples were then ready to be analyzed with the Philips PW 1450/20 AHP X-Ray spectrometer.

According to the principle of X-ray fluorescence spectrometry analysis, three or six U.S.G.S. standards were needed as an analytical background for the calibration of the major oxides and the trace element determinations (Flanagan,1969). In this study, three standards (SCO,SDC,STM) were used for calibrating the major oxides analysis because they have similar amounts of loss on ignition if compared with the sediment samples. For trace element study, six powdered-pellet standards (AGV,G2,GSP, RGM,P-B and SDC) were used for calibrating the background as they have similar ranges with the lake sediments studied.

Original reading from the Philips PW 1450/20 spectrometer was expressed by number (counts per second), and was recorded on tape. Afterwards, through the conversion by a computer program, the results of analysis were expressed in percentage for major oxides and ppm for trace elements.

## Grain Size Analysis

The samples for the particle size analysis were freeze-dried to deflocculate the sediment grains completely. The oven-dried samples were not suitable because they were too highly clumped and not disaggregated. The different grain sizes were determined with the Quantimet 720 TV Image following the preparation procedures described by Peach and Perrie (1975). About 0.05-0.1 gram of the sediment was dispersed in a solution with 10% Sodium Hexametaphosphate wetting agent for 3-5 minutes and then mounted on gelatin-coated microscopic slides in the way outlined by Perrie and Peach (1973). Although such sample amounts were necessarily very small, they were sufficiently large to ensure stability of the statistics associated with the Quantimet measurement (Swift et al., 1972).

Furthermore, the gelatin-coated slides method of mounting the grains results in even dispersal of the sediments on the surface of the slide and avoids "clumping" or "grouping" of the grains making the slides suitable for microscope observation or measurement with the Quantimet. No cover glasses were used on the prepared slides. This method has been proven satisfactory for measuring those grains within very closely spaced units in the fine sediments. Six size fractions were chosen, dependent on the analytical limit and sediment size characteristics; the fractions were 1-2, 2-4, 4-8, 8-16, 16-32 and 32-64 microns.

Clay percentage and silt percentage of cores P-1, P-7, and S-1

$\bar{X}$ : Mean values

(continued)

# APPENDIX IV

Q<sub>1</sub>Q<sub>2</sub>Q<sub>3</sub> Indices, sorting coefficients, and skewness of cores P-1, P-7, and H-1

P-1

P-7

H-1

Sample Number	Q <sub>1</sub> Q <sub>2</sub> Q <sub>3</sub> Indices	S.C.	SKg	Sample Number	Q <sub>1</sub> Q <sub>2</sub> Q <sub>3</sub> Indices	S.C.	SKg	Sample Number	Q <sub>1</sub> Q <sub>2</sub> Q <sub>3</sub> Indices	S.C.	SKg
# 1	6.3,7.2,8.0	1.13	0.97	# 1	7.2,8.0,8.7	1.10	0.98	#130	7.0,8.0,8.7	1.12	0.95
# 4	7.5,8.2,8.7	1.08	0.97	# 3	7.3,7.9,8.7	1.09	1.02	#150	6.6,7.7,8.6	1.14	0.96
# 7	7.6,8.4,8.7	1.08	0.95	# 5	7.1,7.9,8.6	1.10	0.98	#200	7.1,8.0,8.7	1.11	0.96
# 9	8.0,8.5,8.8	1.05	0.97	# 7	7.0,7.9,8.7	1.11	0.98	#230	7.1,8.2,8.7	1.11	0.92
#11	7.7,8.2,8.9	1.07	1.02	# 9	7.1,8.2,8.7	1.11	0.92	#250	7.0,8.0,8.8	1.12	0.96
#13	7.5,8.3,8.7	1.08	0.95	#11	6.9,8.0,8.6	1.12	0.93	#270	6.7,7.9,8.7	1.14	0.93
#16	8.2,8.5,9.2	1.06	0.94	#13	6.9,7.9,8.7	1.12	0.96	#300	6.7,7.6,8.1	1.10	0.94
#18	7.9,8.5,9.1	1.07	0.99	#15	7.0,7.9,8.6	1.11	0.96	#350	7.3,8.0,8.8	1.10	1.00
#20	7.9,8.6,8.9	1.06	0.95	#18	6.9,8.0,8.7	1.12	0.94	#400	7.1,8.0,8.8	1.11	0.98
#22	7.7,8.4,8.8	1.07	0.96	#20	7.5,8.2,8.8	1.08	0.97	#450	6.6,7.8,8.8	1.15	0.95
#24	8.0,8.5,9.1	1.07	1.01	#23	7.1,8.0,8.6	1.10	0.95	#490	7.3,8.2,8.7	1.09	0.94
#26	7.6,8.4,8.8	1.07	0.95	#25	6.9,8.1,8.7	1.12	0.91	#530	7.5,8.1,8.7	1.08	0.99
#27	7.8,8.5,9.1	1.08	0.98	#29	7.0,7.7,8.3	1.09	0.98				
#28	7.4,8.2,8.8	1.09	0.97	#30	7.6,8.2,8.8	1.08	0.99				
#29	7.2,8.1,8.7	1.10	0.95	#32	7.1,7.9,8.5	1.09	0.97				
#30	7.5,8.2,8.8	1.08	0.98	#34	7.6,8.3,8.9	1.08	0.98				
#31	7.6,8.4,8.9	1.08	0.96	#37	7.0,7.9,8.4	1.11	0.98				
#32	7.5,8.3,8.8	1.08	0.96	#40	7.1,7.8,8.4	1.09	0.98				
#34	7.6,8.3,8.8	1.08	0.97	#42	7.0,8.0,8.7	1.11	0.95				
#35	7.2,8.1,8.7	1.10	0.95	#44	7.3,8.2,8.8	1.10	0.95				
#37	7.5,8.3,8.8	1.08	0.96	#47	7.3,8.1,8.7	1.10	0.97				
#39	7.1,8.0,8.7	1.11	0.96	#50	7.5,8.2,8.7	1.09	0.97				
#40	6.4,7.2,8.3	1.14	1.02	#51	7.3,8.1,8.7	1.08	0.97				
				#52	7.6,8.4,8.9	1.09	0.97				
				#54	7.5,8.0,8.7	1.09	1.02				
				#57	7.3,8.2,8.6	1.08	0.93				
				#60	7.5,8.2,8.7	1.08	0.99				

S.C.= Sorting Coefficient=  $\sqrt{Q_3/Q_1}$

SKg= Skewness=  $Q_1 \cdot Q_3 / Q_2^2$

SKa=  $(Q_1 + Q_3 - 2Md) / 2$  Md=  $Q_2$

Sk<sub>g</sub>= Geometric skewness

Sk<sub>a</sub>= Arithmetic skewness

# APPENDIX V

## Geochemical results of lake sediments from Georgian Bay

	#701	#702	#703	#705	#706	#707	#708	#709	#710	#711	#712	#713
SiO <sub>2</sub>	59.51	59.99	58.08	59.17	59.72	59.92	59.95	60.35	60.87	61.01	59.83	61.18
Al <sub>2</sub> O <sub>3</sub>	12.85	13.28	13.05	13.07	13.25	13.24	12.53	13.60	13.34	13.33	13.38	13.66
ΣFeO	6.50	6.35	6.51	6.94	6.31	6.39	6.16	5.49	6.15	6.05	5.86	6.48
MgO	2.07	2.01	2.09	2.05	2.15	1.99	2.19	2.17	2.14	2.13	2.00	2.32
CaO	1.70.	1.75	1.70	1.69	1.76	1.80	1.80	1.83	1.81	1.80	1.80	1.80
Na <sub>2</sub> O	0.97	1.31	1.41	1.39	1.34	1.35	1.18	1.07	1.62	0.51	----	0.01
K <sub>2</sub> O	2.71	2.85	2.74	2.82	2.77	2.74	2.85	2.90	2.84	2.82	2.81	2.81
TiO <sub>2</sub>	0.76	0.78	0.78	0.77	0.79	0.78	0.80	0.80	0.79	0.78	0.78	0.79
MnO	0.09	0.16	0.12	0.17	0.12	0.09	0.08	0.02	0.09	0.14	----	0.07
P <sub>2</sub> O <sub>5</sub>	0.55	0.49	0.66	0.56	0.47	0.51	0.40	0.34	0.36	0.20	0.25	0.25
L.O.I.	13.67	12.61	13.10	12.90	12.59	13.00	13.09	12.32	12.25	12.42	12.41	12.45
% TOTAL	101.38	101.24	100.23	100.50	101.27	101.81	102.03	100.88	102.26	101.19	99.12	101.81
Ba	498.5	439.8	401.3	426.0	411.4	461.5	501.3	407.5	489.4	386.4	484.0	491.6
Zr	158.6	173.4	159.4	155.6	177.4	174.6	174.4	178.9	179.2	189.2	188.3	186.7
Sr	212.3	200.7	183.8	185.7	191.3	199.6	202.0	206.1	201.0	198.2	205.2	197.5
Y	29.4	29.4	27.0	28.0	30.1	29.9	29.2	28.5	29.3	29.1	27.3	29.4
Zn	109.2	106.8	111.9	111.8	111.5	110.1	108.3	111.0	111.9	104.3	107.0	107.9
Cu	47.0	56.7	50.0	54.7	54.6	54.0	53.1	53.5	49.6	62.7	60.4	63.3
Ni	63.2	69.3	64.0	62.4	70.0	68.1	66.8	65.5	63.0	66.4	63.7	64.2
Rb	90.8	95.4	93.3	94.5	93.4	91.6	91.7	96.0	98.3	94.2	93.0	92.0
Ce	92.1	111.0	126.0	113.0	81.6	99.0	72.9	70.9	60.7	127.9	84.2	63.9
S	3453.0	3276.0	3504.0	3139.0	3561.0	3736.0	3845.0	3884.0	3658.0	3692.0	3710.0	3576.0

(continued)

# APPENDIX V

## Geochemical results of lake sediments from Georgian Bay

	#715	#716	#717	#718	#719	#720	#721	#722	#723	#725	#726	#728
SiO <sub>2</sub>	59.47	59.47	61.13	58.54	57.50	58.61	58.34	57.73	58.52	56.26	58.30	55.32
Al <sub>2</sub> O <sub>3</sub>	13.30	13.14	13.51	13.63	13.80	14.44	14.66	14.62	15.04	14.55	15.56	14.64
ΣFeO	6.42	6.07	6.02	5.90	6.28	6.62	6.44	6.66	6.39	7.40	6.48	8.88
MgO	2.12	1.81	2.47	1.83	2.32	2.23	2.32	2.89	2.71	2.70	3.27	3.05
CaO	1.80	1.78	1.85	1.73	1.72	1.76	1.79	1.80	1.88	2.00	2.26	2.85
Na <sub>2</sub> O	0.43	2.33	0.08	0.34	0.37	0.21	0.89	0.85	1.91	0.25	----	2.59
K <sub>2</sub> O	2.85	2.81	2.84	2.93	3.04	3.27	3.27	3.38	3.47	3.33	3.39	3.33
TiO <sub>2</sub>	0.78	0.77	0.79	0.79	0.80	0.82	0.83	0.83	0.85	0.83	0.85	0.82
MnO	0.11	0.05	0.04	0.04	0.11	0.08	0.11	0.09	0.12	0.05	0.05	0.38
P <sub>2</sub> O <sub>5</sub>	0.21	0.19	0.19	0.23	0.20	0.21	0.28	0.61	0.24	2.73	0.17	1.11
L.O.I.	14.09	13.43	13.45	13.89	13.57	12.67	12.15	12.11	10.55	10.58	9.98	7.76
% TOTAL	101.59	101.85	102.36	99.85	99.72	100.92	101.07	101.54	101.67	100.69	100.32	100.74
Ba	575.8	567.4	513.2	508.4	511.9	531.3	594.4	552.3	555.7	675.3	579.8	677.1
Zr	170.1	179.8	180.0	168.6	169.1	172.2	177.5	172.3	166.9	173.0	190.5	171.9
Sr	200.6	198.0	206.2	196.9	195.7	197.6	204.5	199.4	201.3	204.2	212.5	214.0
Y	28.8	29.4	27.9	27.3	29.1	29.9	28.8	29.4	27.4	28.6	29.4	29.8
S	4006.0	3607.0	3289.0	3830.0	4079.0	3008.0	3431.0	2663.0	2190.0	2057.0	1881.0	1230.0
Zn	108.0	114.4	108.5	110.5	108.5	104.6	104.6	101.4	98.8	93.7	96.7	101.4
Cu	62.4	66.4	59.3	60.9	64.0	55.5	60.3	58.1	48.4	43.1	43.6	45.7
Ni	69.9	66.0	61.4	66.6	69.0	69.8	65.8	68.2	64.0	61.5	65.7	72.8
Rb	96.8	96.4	97.3	97.6	102.7	104.1	108.6	108.2	115.2	102.8	112.8	118.5
Ce	90.7	94.5	92.4	93.2	67.0	108.4	70.2	98.3	59.1	95.7	105.9	114.4

(continued)

# APPENDIX V

## Geochemical results of lake sediments from Georgian Bay

	#729	#730	#731	#732	#734	#735	#736	#737	#738	#739	#740	#741
SiO <sub>2</sub>	57.89	56.80	56.66	57.13	58.79	59.05	59.75	59.42	58.36	58.23	57.83	57.28
Al <sub>2</sub> O <sub>3</sub>	16.51	15.61	16.08	16.36	15.71	16.39	15.74	16.24	15.89	15.97	15.83	15.42
ΣFeO	8.00	6.80	6.87	6.75	6.52	5.88	6.31	6.19	6.55	6.49	6.30	7.26
MgO	3.30	2.90	2.68	2.76	2.91	2.56	2.84	2.70	2.53	2.67	2.78	2.77
CaO	1.78	1.78	1.86	1.86	1.93	2.08	2.05	2.00	1.93	2.00	3.16	3.61
Na <sub>2</sub> O	----	1.30	1.58	1.15	0.38	1.27	0.91	1.47	2.99	2.50	1.64	0.19
K <sub>2</sub> O	3.66	3.42	3.53	3.57	3.52	3.52	3.50	3.52	3.58	3.61	3.39	3.35
TiO <sub>2</sub>	0.80	0.79	0.82	0.82	0.82	0.85	0.84	0.86	0.84	0.84	0.87	0.82
MnO	0.09	0.16	----	0.06	0.11	----	0.13	0.09	0.18	0.06	0.13	0.11
P <sub>2</sub> O <sub>5</sub>	0.41	0.30	0.53	0.51	0.38	0.40	0.29	0.51	0.47	0.37	0.43	0.27
L.O.I.	6.70	9.06	7.17	7.02	7.70	7.43	7.46	7.30	7.17	7.51	9.38	9.49
% TOTAL	99.15	98.93	97.78	97.98	98.77	99.43	99.80	100.30	100.50	100.27	101.73	100.57
Ba	432.3	657.9	649.2	740.2	561.1	693.4	743.6	680.4	577.1	698.5	565.9	627.4
Zr	161.0	178.1	168.9	173.0	167.1	172.8	168.9	166.1	171.0	168.6	165.5	147.7
Sr	197.1	212.6	220.4	223.2	212.2	229.8	228.8	227.7	228.1	228.2	236.4	219.5
Y	29.2	28.5	29.2	28.6	30.0	27.9	29.0	28.8	29.7	28.4	27.8	24.8
S	600.0	641.0	630.0	663.0	755.0	797.0	902.0	901.0	1090.0	1070.0	1739.0	1337.0
Zn	106.3	103.6	103.6	104.4	101.9	98.6	99.2	98.2	97.3	96.8	101.3	94.8
Cu	41.9	41.9	42.1	43.7	47.3	44.2	47.3	45.7	44.7	41.1	41.4	32.1
Ni	74.8	71.0	64.9	70.4	68.0	67.9	70.7	64.1	67.7	68.1	65.3	63.5
Rb	127.8	120.0	125.9	127.5	118.0	114.9	118.1	115.7	121.5	117.5	108.5	107.9
Ce	84.9	67.8	67.6	116.7	112.6	92.4	84.9	62.0	123.3	74.8	86.1	116.8

(continued)



## APPENDIX V

## Geochemical results of lake sediments from Georgain Bay

	#743	#745	#748	#750	#751	#753	#754	#757	#758	#759	#760
SiO <sub>2</sub>	56.95	58.17	59.15	58.12	58.21	57.33	55.44	57.74	57.37	57.73	57.52
Al <sub>2</sub> O <sub>3</sub>	16.04	17.43	17.18	16.24	16.63	16.53	15.99	16.71	16.91	16.30	16.63
ΣFeO	7.60	7.82	7.82	7.86	8.19	8.43	9.19	8.90	8.85	8.79	8.69
MgO	3.10	2.99	2.96	2.79	2.84	3.04	2.99	2.95	2.89	3.04	2.86
CaO	2.06	1.87	1.84	1.81	1.76	1.72	1.89	1.71	1.76	1.83	1.78
Na <sub>2</sub> O	1.09	1.68	0.93	1.77	1.06	1.40	1.89	1.41	1.70	1.21	1.42
K <sub>2</sub> O	3.47	3.57	3.55	3.48	3.60	3.54	3.85	3.54	3.59	3.69	3.58
TiO <sub>2</sub>	0.84	0.81	0.80	0.78	0.77	0.78	0.78	0.79	0.80	0.80	0.80
MnO	0.11	0.15	0.07	0.10	0.06	0.06	0.02	0.06	0.01	0.01	0.04
P <sub>2</sub> O <sub>5</sub>	0.26	0.61	0.23	0.65	0.93	0.75	1.02	0.81	0.97	0.86	0.83
L.O.I.	6.90	7.30	7.15	7.06	7.81	7.17	7.49	7.59	7.48	7.52	8.17
% TOTAL	98.42	102.40	101.67	100.65	101.86	100.75	100.57	102.21	102.32	101.75	102.31
Ba	742.4	717.9	627.7	608.1	685.7	641.7	705.1	619.1	637.1	646.8	565.2
Zr	176.4	159.5	161.4	162.8	159.5	156.2	154.0	150.2	151.0	153.6	150.4
Sr	226.1	216.4	211.7	209.5	197.1	190.7	200.0	195.7	198.1	200.0	197.3
Y	28.7	29.7	29.2	29.1	29.0	29.9	28.1	28.9	28.7	27.4	29.2
S	1055.0	550.0	856.0	578.0	520.0	429.0	456.0	428.0	465.0	455.0	562.0
Zn	104.3	109.2	113.0	110.6	112.4	119.4	110.5	112.1	113.3	112.1	117.5
Cu	43.2	42.2	47.3	47.1	43.9	43.3	42.9	38.4	32.0	32.1	48.5
Ni	68.0	69.6	67.8	72.0	70.8	74.6	74.7	73.1	70.3	67.5	69.9
Rb	113.8	132.1	124.1	131.4	128.0	129.1	130.0	65.2	125.8	128.3	131.9
Ce	48.6	97.8	58.4	105.2	87.2	67.1	77.0	94.1	63.1	89.3	63.8

(continued)

# APPENDIX V

## Geochemical results of lake sediments from Georgian Bay

	#101	#103	#105	#107	#109	#111	#113	#117	#119	#123	#125	#127
SiO <sub>2</sub>	52.98	47.76	49.32	51.06	51.45	47.85	51.72	49.65	47.64	48.57	47.85	48.09
Al <sub>2</sub> O <sub>3</sub>	13.52	13.09	17.50	16.68	15.73	14.48	15.93	13.36	14.27	12.65	13.23	12.65
ΣFeO	5.82	5.73	9.83	9.99	8.74	7.28	7.80	5.25	6.28	5.11	5.42	5.13
MgO	4.28	4.51	3.83	3.98	4.21	4.18	3.97	4.39	4.22	4.41	4.46	4.27
CaO	6.23	8.80	2.80	3.06	4.26	7.72	5.57	9.78	10.44	11.56	10.59	11.43
Na <sub>2</sub> O	0.98	0.61	0.48	0.67	----	1.35	0.79	1.56	0.01	0.24	0.30	----
K <sub>2</sub> O	3.67	3.68	4.02	3.96	3.92	3.38	3.79	3.40	3.64	3.42	3.50	3.43
TiO <sub>2</sub>	0.81	0.81	0.91	0.89	0.89	0.84	0.87	0.79	0.82	0.80	0.80	0.80
MnO	0.04	0.13	0.19	0.33	0.23	0.05	0.34	0.10	0.32	0.29	0.02	0.06
P <sub>2</sub> O <sub>5</sub>	0.31	0.14	0.17	0.25	0.25	0.35	0.26	0.26	0.28	0.28	0.10	0.28
L.O.I.	13.16	14.71	9.06	8.43	9.37	10.86	9.64	12.86	11.94	12.07	12.05	12.59
% TOTAL	101.80	99.97	98.10	99.32	99.06	98.34	100.70	101.38	99.82	99.40	98.31	98.82
Ba	557.5	504.2	554.6	599.5	568.9	633.7	659.7	588.3	550.0	429.9	519.7	552.9
Zr	136.7	133.2	150.2	135.2	134.4	123.0	147.4	145.6	144.8	155.2	146.7	151.9
Sr	148.3	129.4	138.0	143.7	144.3	204.5	208.3	219.5	222.0	214.1	215.2	219.4
Y	28.4	27.9	29.1	29.0	28.6	24.5	29.3	23.4	26.0	26.0	26.9	27.6
S	1440.0	1235.0	1009.0	4472.0	509.0	387.0	469.0	710.0	618.0	978.0	780.0	470.0
Zn	87.0	77.3	115.4	115.2	103.9	93.9	96.7	76.3	79.1	67.4	70.6	66.4
Cu	29.9	28.3	45.3	44.9	39.9	35.1	38.1	27.7	30.3	26.9	30.1	23.2
Ni	55.9	52.5	78.1	74.2	69.7	64.5	73.7	54.0	58.0	53.5	49.6	51.6
Rb	112.4	119.3	141.1	134.4	132.7	113.3	114.4	102.1	106.7	93.7	90.2	94.4
Ce	84.8	86.7	95.6	85.6	66.0	65.5	70.9	50.9	70.4	93.6	56.6	25.5

(continued)

# APPENDIX V

## Geochemical results of lake sediments from Harts Lake

	#129	#131	#133	#135	#139	#HS-4	#HS-3	#HS-2	#HS-1	#100	#120	#140
SiO <sub>2</sub>	50.32	50.41	51.85	44.16	47.38	61.54	61.39	63.38	60.20	61.62	61.50	61.25
Al <sub>2</sub> O <sub>3</sub>	15.18	14.66	10.39	10.06	11.52	13.05	11.00	11.41	12.20	10.24	10.33	11.71
ΣFeO	6.93	6.22	3.81	3.67	4.11	3.22	2.89	2.87	2.44	2.93	3.30	3.35
MgO	4.09	4.45	4.26	4.90	4.38	0.88	0.98	0.57	1.17	0.82	0.25	1.44
CaO	6.50	8.78	12.94	16.27	14.40	2.27	2.28	2.36	1.77	1.58	2.28	2.40
Na <sub>2</sub> O	2.13	1.69	1.35	----	0.57	2.14	1.50	1.49	0.23	----	0.73	1.15
K <sub>2</sub> O	3.82	3.61	2.87	2.82	3.20	2.47	2.30	2.36	2.28	1.54	2.36	2.31
TiO <sub>2</sub>	0.82	0.82	0.68	0.69	0.75	0.55	0.74	0.74	0.55	0.38	0.75	0.73
MnO	0.12	0.09	0.08	0.16	0.08	0.18	0.03	0.16	0.24	0.15	0.07	0.16
P <sub>2</sub> O <sub>5</sub>	0.23	0.31	0.14	0.22	0.31	0.26	0.37	0.17	0.25	0.20	0.29	0.22
L.O.I.	8.61	10.04	14.02	15.79	13.77	11.66	16.67	13.93	17.67	22.99	18.00	16.49
% TOTAL	98.75	101.09	102.38	98.74	100.46	98.22	100.15	99.44	99.00	102.45	100.83	101.21
Ba	577.2	426.2	653.6	537.1	483.6	644.0	531.1	635.8	370.1	344.0	450.6	584.7
Zr	140.6	150.6	183.1	148.7	144.4	536.0	426.4	431.4	325.4	250.7	312.8	448.7
Sr	242.9	249.8	312.3	245.6	262.3	349.3	315.0	325.7	278.3	233.8	266.4	336.8
Y	29.4	27.5	23.8	22.8	22.1	26.8	28.7	28.6	28.5	28.7	29.1	27.2
S	363.0	600.0	840.0	456.0	1627.0	2340.0	2505.0	2375.0	3103.0	3520.0	2731.0	2310.0
Zn	86.8	80.0	47.8	46.5	55.0	65.8	88.3	85.8	109.9	117.0	96.6	74.1
Cu	36.7	33.8	12.4	12.6	18.4	7.4	12.5	12.6	16.5	39.4	19.2	11.0
Ni	74.7	63.4	40.4	32.3	42.6	30.0	36.8	34.6	37.2	38.5	45.5	36.3
Rb	112.0	106.7	85.2	68.1	83.2	63.6	64.1	63.6	63.9	56.0	66.0	57.1
Ce	80.0	92.8	48.0	71.7	65.3	92.6	102.9	158.0	108.4	110.8	108.6	106.4

(continued)

# APPENDIX V

## Geochemical results of lake sediments from Harts Lake

	#180	#220	#340	#280	#300	#360	#380	#420	#460	#520
SiO <sub>2</sub>	56.29	67.12	62.79	62.39	60.27	58.51	62.16	64.99	64.36	64.36
Al <sub>2</sub> O <sub>3</sub>	14.86	15.16	14.78	15.29	15.82	14.42	14.57	14.29	15.25	14.43
ΣFeO	5.18	5.77	6.02	5.81	5.31	5.74	5.08	4.67	5.37	5.23
MgO	1.44	1.56	2.34	2.18	2.62	3.41	2.69	2.29	2.59	2.01
CaO	2.21	3.19	2.96	3.24	3.43	4.45	3.76	2.99	3.65	2.79
Na <sub>2</sub> O	33.21	1.76	3.84	3.07	2.72	2.37	2.83	1.93	1.95	2.77
K <sub>2</sub> O	2.98	3.08	3.34	3.38	3.34	3.48	3.30	3.26	3.42	3.48
TiO <sub>2</sub>	0.74	0.85	0.83	0.85	0.75	0.85	0.83	0.68	0.90	0.74
MnO	----	0.10	0.22	0.20	0.12	0.05	0.11	----	0.10	0.08
P <sub>2</sub> O <sub>5</sub>	0.27	0.60	0.27	0.31	0.27	0.34	0.26	0.29	0.44	0.24
L.O.I.	11.81	1.96	2.35	3.21	4.12	5.82	3.82	3.43	3.47	3.13
% TOTAL	98.99	101.14	99.72	100.41	98.78	99.45	99.41	98.80	101.5	99.26

Ba	403.1	906.1	1020.4	1011.6	969.3	823.3	1085.7	1007.8	872.0	990.5
Zr	301.4	304.9	296.7	332.3	307.9	237.7	317.3	302.5	218.2	266.6
Sr	268.5	281.5	289.7	302.3	296.7	257.2	328.4	294.7	258.1	317.4
Y	29.4	28.6	26.6	28.7	26.6	27.9	27.6	27.7	26.4	24.5
S	6643.0	183.0	163.0	150.0	147.0	154.0	132.0	137.0	110.0	76.0
Zn	142.7	85.5	84.2	25.0	67.4	66.3	62.2	65.2	79.2	74.3
Cu	84.8	35.1	28.1	69.2	20.5	24.5	22.6	24.0	25.6	13.7
Ni	60.0	69.9	53.3	19.8	43.6	43.6	40.6	41.5	48.9	37.6
Rb	72.7	87.6	84.2	48.7	87.8	90.0	91.5	96.1	98.9	81.6
Ce	91.0	77.4	82.1	80.7	97.0	66.7	85.2	92.1	107.1	94.1

\*\*\*\*\*

Major oxides and L.O.I. are expressed in weight percentage

Trace elements are expressed in parts per million

---- Analysis not determined

## APPENDIX V

## Geochemical results of lake sediments from Shepherd Lake

	#S-60	#S-100	#S-130	#S-150	#S-190	#S-320	#S-340	#S-380	#S-440
SiO <sub>2</sub>	17.02	10.84	11.70	16.56	19.09	19.72	20.13	17.47	15.56
Al <sub>2</sub> O <sub>3</sub>	3.25	2.92	3.70	3.14	4.12	4.73	4.41	4.19	3.73
ΣFeO	0.86	0.72	0.66	0.94	0.70	1.14	0.92	0.85	0.63
MgO	0.29	0.17	0.09	0.74	0.45	0.32	1.31	0.80	0.74
CaO	2.59	2.65	2.72	2.34	2.18	2.34	2.73	3.16	2.91
Na <sub>2</sub> O	0.93	0.03	0.18	0.36	0.70	0.56	0.77	0.28	0.28
K <sub>2</sub> O	0.38	0.35	0.60	0.55	0.45	0.58	0.50	0.53	0.29
TiO <sub>2</sub>	0.20	0.17	0.27	0.16	0.14	0.16	0.13	0.16	0.08
MnO	----	----	0.09	0.10	----	0.30	0.05	0.02	0.02
P <sub>2</sub> O <sub>5</sub>	0.11	0.11	0.12	0.20	0.15	0.16	0.15	0.15	0.14
L.O.I.	76.56	83.69	73.76	76.57	72.41	72.21	70.22	72.62	75.32
%	102.18	101.66	101.88	101.66	100.39	102.22	98.59	100.23	99.70
	#S-480	#S-510	#S-530	#S-610	#S-720	#S-760	#S-800	#S-840	#S-880
SiO <sub>2</sub>	10.89	8.26	13.28	13.16	29.81	25.76	47.06	55.75	50.47
Al <sub>2</sub> O <sub>3</sub>	4.32	4.37	4.40	5.09	8.13	7.59	8.74	11.06	9.18
ΣFeO	1.17	1.18	0.97	1.38	4.90	4.02	3.90	3.84	1.59
MgO	0.63	0.51	0.50	0.86	0.59	0.76	1.05	4.56	5.42
CaO	2.34	3.09	2.59	2.78	2.89	2.08	2.27	6.34	12.43
Na <sub>2</sub> O	----	1.40	0.17	0.38	3.00	0.83	0.83	1.36	1.85
K <sub>2</sub> O	0.48	0.37	0.47	0.63	1.33	1.37	1.83	2.62	1.95
TiO <sub>2</sub>	0.14	0.10	0.13	0.18	0.29	0.34	0.43	0.52	0.29
MnO	0.02	----	0.05	0.04	0.04	0.21	0.02	0.09	0.03
P <sub>2</sub> O <sub>5</sub>	0.17	0.31	0.12	0.20	0.34	0.24	0.29	0.19	0.20
L.O.I.	81.89	81.14	79.21	76.55	50.20	57.57	32.23	13.89	16.06
%	102.05	100.71	101.89	101.25	101.51	100.75	98.65	100.22	99.47

## APPENDIX VI

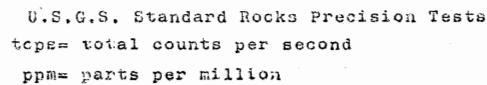
The Phillips PW 1420 parameters used for the analysis of the major elements are listed below.

MAJOR ELEMENT PARAMETERS										
<u>Element</u>	<u>Det.</u>	<u>Coll.</u>	<u>Crystal</u>	<u>2<math>\theta</math><sup>o</sup> Pk</u>	<u>2<math>\theta</math><sup>o</sup> Bkg</u>	<u>Count Time</u>	<u>LL</u>	<u>Window</u>	<u>kV</u>	<u>mA</u>
Si	Flow	coarse	PET	109.42	108.70	4	250	500	50	45
Al	Flow	coarse	PET	145.48	144.37	10	200	800	50	45
Fe	Flow	fine	LiF200	57.52	56.50	4	150	750	50	45
Mg	Flow	coarse	TLAP	45.37	44.83	20	250	700	50	45
Ca	Flow	coarse	LiF200	113.35	114.85	2	50	600	50	45
Na	Flow	coarse	TLAP	55.27	55.05	20	300	400	50	45
K	Flow	coarse	LiF200	136.94	135.60	10	300	400	50	45
Ti	Flow	coarse	LiF200	86.30	85.20	10	250	700	50	45
Mn	Flow	fine	LiF200	56.65	56.84	20	150	750	60	45
P	Flow	coarse	CE	141.16	140.54	10	200	800	50	45

The Phillips PW 1420 parameters used for analysis of the trace elements are presented below.

MINOR ELEMENT PARAMETERS										
<u>Element</u>	<u>Det.</u>	<u>Coll.</u>	<u>Crystal</u>	<u>2 <math>\theta</math><sup>o</sup> Pk</u>	<u>2 <math>\theta</math><sup>o</sup> Bkg</u>	<u>Count Time</u>	<u>LL</u>	<u>Window</u>	<u>kV</u>	<u>mA</u>
Ba	Scint.	Fine	LiF200	11.02	11.50	20	250	500	50	45
Ce	Scint.	Fine	LiF200	10.22	9.22	40	250	500	50	45
Cu	Scint. + Flow	Coarse	LiF200	45.10	45.60	40	300	400	60	45
Ni	Scint. + Flow	Coarse	LiF200	48.78	48.00	40	250	500	60	45
Rb	Scint.	Fine	LiF200	26.30	26.57	20	300	400	50	45
S	Flow	Coarse	GE	109.20	110.79	20	200	800	50	45
Sr	Scint.	Fine	LiF200	25.12	24.75	20	250	500	50	45
Y	Scint.	Fine	LiF200	23.72	23.50	20	250	500	60	45
Zn	Scint. + Flow	Coarse	LiF200	41.90	41.20	40	300	400	60	45
Zr	Scint.	Fine	LiF200	22.48	22.95	20	300	400	50	45

Trace element analysis of the standard rocks are presented below in graph form.



## APPENDIX VI

The statistical tests of the standard rocks for the trace elements are presented below where,  $r$  = correlation coefficient,  $s(x,y)$  = standard limit of error and  $y$  = least squares solution of the equation of the line.

<u>Nickel ( Ni )</u>	<u>Copper ( Cu )</u>	<u>Zinc ( Zn )</u>
$r = 0.99$	$r = 0.93$	$r = 0.94$
$s(x,y) = 10.79$	$s(x,y) = 8.66$	$s(x,y) = 14.39$
$y = 0.12x - 17.28$	$y = 0.11x - 42.65$	$y = 0.07x + 23.02$
<u>Rubidium ( Rb )</u>	<u>Strontium ( Sr )</u>	<u>Zirconium ( Zr )</u>
$r = 0.97$	$r = 0.98$	$r = 0.97$
$s(x,y) = 18.40$	$s(x,y) = 50.12$	$s(x,y) = 47.76$
$y = 0.30x + 5.30$	$y = 0.33x - 18.01$	$y = 0.13x + 78.20$
<u>Yttrium ( Y )</u>	<u>Barium ( Ba )</u>	<u>Cerium ( Ce )</u>
$r = 0.74$	$r = 0.98$	$r = 0.91$
$s(x,y) = 9.33$	$s(x,y) = 129.73$	$s(x,y) = 54.56$
$y = 0.09x + 6.38$	$y = 1.57x + 58.02$	$y = 3.46x - 167.13$

A minimum of 6 U.S.G.S. standards were rerun after 12 unknown samples to maintain proper precision limits.