**HOLOCENE ENVIRONMENTAL HISTORY OF LAKE WINNIPEG:
THECAMOEBIANS AND STABLE LEAD ISOTOPES**

by

SUSAN M. BURBIDGE, BSC (HONS.), MSC

A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

Department of Earth Sciences, Carleton University
and the Ottawa-Carleton Geoscience Centre
Ottawa, Ontario

August 29, 1997

National Library
of Canada

Acquisitions and
Bibliographic Services

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale
du Canada

Acquisitions et
services bibliographiques

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence

Our file Notre référence

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

0-612-26848-9

Carleton University
Ottawa, Canada K1S 5J7

1942-1992

Thesis contains black and white and/or coloured graphs/tables/photographs which when microfilmed may lose their significance. The hardcopy of the thesis is available upon request from Carleton University Library.

ABSTRACT

This study is a paleolimnological and detailed taxonomic account of the thecamoebian fauna and stable lead isotopic composition of Lake Winnipeg sediments. Holocene sediments in Lake Winnipeg consist of the lower Lake Agassiz sequence unconformably overlain by the Lake Winnipeg sequence. Nine piston/gravity core sites and three box core sites, covering the North and South basins and the connecting Narrows, were selected for analysis.

The identification of thecamoebians is complicated by their wide range of intra- and interspecific variability. The term strain is introduced for designating intraspecific variations in thecamoebians. Strains were assigned previously published names according to the original designation and/or commonly accepted synonymy in order to facilitate comparison between studies.

The paleolimnological study indicates that biologic productivity and consequently the type of organic material in the sediments is the main control on thecamoebian distribution. Other factors are water chemistry and turbidity whereas inorganic sediment geochemistry and water temperature do not appear to significantly influence the thecamoebian fauna.

Variations in abundance of key thecamoebian species along a north-south transect divide Lake Winnipeg into three distinct areas. Environmental changes are more significant in the restricted South Basin, resulting in distinct thecamoebian assemblages. In contrast, the North Basin provided a more stable environment throughout the late Holocene.

Stable lead isotope composition can yield information on sources of lead in lake sediments. In this reconnaissance study, lead isotopic compositions were determined for acid-soluble and residual sediment fractions of samples from a north-south transect of Lake Winnipeg. Results show that lead in the sediment is derived from natural and anthropogenic sources and both interbasinal and vertical variations in source material can be distinguished.

The natural-source lead in Lake Winnipeg sediments was predominantly derived from the Superior Province (model age 2.5 Ga). The North Basin sediment contains lead which was derived directly from Archean granitic rocks. In the South Basin common lead was derived from the Superior Province but recycled through Paleozoic and Mesozoic sedimentary rock before entering Lake Winnipeg.

Reduced isotopic ratios of acid-soluble lead are indicative of anthropogenic lead sources in the most recent sediments. Specific sources of anthropogenic lead for Lake Winnipeg cannot be determined with the present data since the anthropogenic isotopic composition is unknown.

ACKNOWLEDGMENTS

First and foremost, I would like to thank Dr. Claudia Schröder-Adams for her constant encouragement, scientific discussion and advice, financial support and, most importantly, her friendship. I also want to thank Dr. John Blenkinsop for his motivation, support and scientific discussions of the lead isotope project.

The research was partially funded by a research grant of the Natural Sciences and Engineering Research Council of Canada to C.J. Schröder-Adams and NSERC and OGS postgraduate scholarships to S.M. Burbidge. Funding for the isotopic and geochemical analyses was provided by Dr. J. Blenkinsop.

I am grateful to the shipboard scientists and crew of the CCGS Namao and the helpful staff of the GSC (Dartmouth) Core Facility for supplying the samples. In particular, I would like to thank Mike Lewis, Harvey Thorleifson and Brian Todd for giving me the opportunity to join this project. I wish to thank Brian Cousens for his technical assistance in the clean lab and infinite patience in teaching me to use the mass spectrometer. He was very generous with his time and I am most grateful for all his help. Assistance on the SEM was provided by C. Huang, P. Jones and L. Ling. Harvey Thorleifson and Penny Henderson provided helpful discussions for which I am very grateful. I would also like to thank Dr. D. Charles for his critical review of the paleolimnology manuscript (Chapter 4).

My friends in “the carbs club” are greatly appreciated for their moral support and good cheer. A special note of thanks goes to Catharine and David Farrow and Sam Alpay, whose friendship and encouragement has sustained me through this research project. I also wish to thank Sheila Thayer for helping me through the bureaucratic maze and for popcorn.

Finally, I would like to thank the people who mean the most to me, my family. I will be forever grateful for the encouragement, patience, and support of Mar and Gorgeous; I dedicate this thesis to them.

Materials and Methods

TABLE OF CONTENTS

	Page
Acceptance Sheet	ii
Abstract	iii
Acknowledgments	v
Table of Contents	vi
List of Tables	ix
List of Figures	x
List of Appendices	xii
 CHAPTER 1. INTRODUCTION	 1
Previous Work	1
The Lake Winnipeg Project (Phase 1)	2
Objectives of this Study	3
Original Contribution	5
 CHAPTER 2. LAKE WINNIPEG: PAST AND PRESENT	 7
Geologic Setting	7
Quaternary Basin History	10
Sediments of Lake Winnipeg	13
Water Column Analyses	14
Chronology	14
 CHAPTER 3. HOLOCENE THECAMOEBIANS OF LAKE WINNIPEG, MANITOBA, CANADA	
Abstract	34
Introduction	35
General Characteristics of Thecamoebians	36
Location	39

Materials and Methods	41
Taxonomic Approach	42
General Observations	43
Systematic Paleontology	43
Acknowledgments	71

CHAPTER 4. THECAMOEBIANS IN LAKE WINNIPEG:

A TOOL FOR HOLOCENE PALEOLIMNOLOGY

Abstract	88
Introduction	90
Location	91
Materials and Methods	93
Taxonomic Approach	94
Results	95
North Basin	95
The Narrows	97
South Basin	98
Discussion	99
Conclusions	105
Acknowledgments	106

CHAPTER 5. SOURCES OF LEAD IN HOLOCENE LAKE WINNIPEG

SEDIMENTS: EVIDENCE FROM STABLE LEAD

ISOTOPIC ABUNDANCES

Abstract	130
Introduction	131
Lead Isotopes	132
Materials and Methods	134
Results and Discussion	136

Conclusions	142
CHAPTER 6. CONCLUSIONS	157
REFERENCES	159
APPENDICES	183

LIST OF TABLES

TABLE	DESCRIPTION	PAGE
2-1	Temperature and Secchi depth measurements from the grab sampling survey	17
4-1	Summary of thecamoebian occurrence in the Lake Winnipeg sequence as percent abundance	108
4-2	Mean percent abundance, associated standard deviation and range of percent abundance of diagnostic species for each thecamoebian assemblage	111
5-1	Isotopic compositions of acid-soluble and residual lead	144
5-2	Isotopic composition of lead in Quaternary lake sediments from adjacent drainage systems of the Canadian Shield	146

LIST OF FIGURES

FIGURE	DESCRIPTION	PAGE
2-1	Simplified map showing the location of Lake Winnipeg and the major rivers of the catchment	19
2-2	Geological map of Manitoba	21
2-3	Regional structural cross section showing Paleozoic to Cenozoic formations in southern Manitoba	23
2-4	Location of piston/gravity core and box core sites	25
2-5	Generalized lithology of sediment cores of Lake Winnipeg	27
2-6	Location of sampling survey stations for water column analysis	29
2-7	Temperature-depth profiles for selected locations in Lake Winnipeg	31
2-8	Secular age models for the North and South basins	33
3-1	Location map showing coring sites selected for thecamoebian analyses	73
3-2	<u>Arcella vulgaris</u> , <u>Centropyxis aculeata</u> “aculeata”, <u>Centropyxis aculeata</u> “discooides”, <u>Centropyxis aculeata</u> “ecornis”, <u>Centropyxis constricta</u> , <u>Diffflugia protaeiformis</u> “protaeiformis”, and <u>Diffflugia protaeiformis</u> “elegans”	75
3-3	<u>Diffflugia protaeiformis</u> “inflata”, <u>Diffflugia ampullula</u> , <u>Diffflugia fragosa</u> “fragosa”, <u>Diffflugia fragosa</u> “strain a” and <u>Diffflugia globulus</u>	77
3-4	<u>Diffflugia manicata</u> , <u>Diffflugia oblonga</u> “oblonga”, <u>Diffflugia oblonga</u> “lacustris”, <u>Diffflugia oblonga</u> “lanceolata”, and <u>Diffflugia oblonga</u> “linearis”	79
3-5	<u>Diffflugia manicata</u> , <u>Diffflugia urceolata</u> “urceolata”, <u>Diffflugia urceolata</u> “amphora”, <u>Diffflugia urceolata</u> “lebes”, and <u>Cucurbitella corona</u>	81
3-6	<u>Diffflugia urens</u> , <u>Diffflugia viscidula</u> , <u>Lagenodifflugia vas</u> , <u>Pontigulasia compressa</u> , and <u>Cucurbitella tricuspis</u>	83
3-7	<u>Awerintzewia cyclostoma</u> , <u>Heleopera sphagni</u> , <u>Lesquereusia spiralis</u> ,	

	<u>Oopyxis</u> sp., <u>Trigonopyxis arcula</u> , and <u>Cyclopyxis arcelloides</u>	85
3-8	Illustration of <u>Phryganella acropodia</u> and <u>Euglypha alveolata</u>	87
4-1	Location map showing coring sites selected for thecamoebian analyses	113
4-2	Lithologic column and abundance diagrams for important thecamoebian species in North Basin Core 103	115
4-3	Lithologic columns and distribution curves of important thecamoebian species for North Basin cores 104a and 105	117
4-4	Lithologic columns and distribution curves of important thecamoebian species in North Basin Cores 106 and 107	119
4-5	Lithologic columns and distribution curves of important thecamoebian species for cores 110a and 113a north and south of The Narrows	121
4-6	Lithologic column and distribution curves of important thecamoebian species in Core 120 in the South Basin	123
4-7	Lithologic column and distribution curves of important thecamoebian species in Core 122a from the South Basin	125
4-8	Summary of the distribution of thecamoebian assemblages	127
4-9	SEM images of selected thecamoebian species	129
5-1	Location map showing sample locations for lead analyses and generalized bedrock geology	148
5-2	Plot of $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ for all Lake Winnipeg samples	150
5-3	Distribution of $^{206}\text{Pb}/^{207}\text{Pb}$ with depth	152
5-4	Plot of $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ for residual sediments	154
5-5	Plot of $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$ showing the Stacey-Krammers Model growth curve	156

LIST OF APPENDICES

APPENDIX	DESCRIPTION	PAGE
1-1	Gravity/piston and box core data	183
4-1	Thecamoebian Faunal List	184
5-1	Decay Series of Uranium and Thorium	187
5-2	Correction factors used to compensate for machine fractionation of measured isotopic ratios	188

CHAPTER 1.

INTRODUCTION

Lake Winnipeg is a major feature on the Canadian landscape and could be considered the sixth Great Lake. Covering a surface area larger than Lake Ontario and only slightly smaller than Lake Erie, it is the eleventh largest lake in the world (Todd and Lewis, 1996). A constriction called The Narrows divides the lake into two basins, a large North Basin and much smaller South Basin. Hydrographic charting indicates that the offshore lakebed is quite flat and shallow; water depths average about 16 m in the North Basin and 9 m in the South Basin.

Lake Winnipeg is of great importance to Manitoba's economy. The South Basin, with its sandy beaches, is used extensively for cottage development and recreation (Hans and Doering, 1995). The lake also has significant commercial activities such as fisheries and generation of hydroelectric power. Lake Winnipeg is Manitoba Hydro's most important reservoir as two thirds of the water used to generate Manitoba's hydroelectricity passes through Lake Winnipeg (Raban, 1995).

Previous work

Despite its economic importance, there has been a paucity of research on Lake Winnipeg. Various land-based surveys have examined the Quaternary geology, surficial sediments and beaches of the region surrounding Lake Winnipeg (Dowling, 1900; Tyrrell and Dowling, 1900; Klassen, 1967; Tarnocae, 1970; Groom, 1985; Matile and Groom, 1987; Nielsen, 1989; Henderson, 1994). Most of these studies are concerned with sediments from Lake Agassiz, the post-glacial predecessor of Lake Winnipeg which covered much of Manitoba during the early Holocene.

In addition to the land-based research, some offshore investigations have been conducted. Early studies recorded relatively clear waters in the North Basin and muddy waters in the South Basin caused by deposition and resuspension of copious sediments

from the Red River (Upham, 1890). During the last century, a few investigations have focused on chemistry, mineralogy and grain size of Lake Winnipeg sediment, notably in the form of unpublished MSc. theses (Ward, 1926; Kushnir, 1971) and unpublished government manuscript reports (Brunskill and Graham, 1979). Limited limnological studies of the North and South basins have also been presented in government reports (Rybicki, 1966; Crowe, 1973; Brunskill et al., 1979a, 1979b; Brunskill et al., 1980). In addition, various biologically-based investigations were conducted which examined the phytoplankton, zooplankton and macrobenthos of Lake Winnipeg (Lowe, 1924; Bajkov, 1930, 1934; Patalas and Salki, 1992; Flannagan et al., 1994).

Of these limited land-based and lake studies, the only multidisciplinary effort was a limnological survey led by the Freshwater Institute of Fisheries and Oceans Canada in 1969 (Brunskill and Graham, 1979; Brunskill et al., 1979a, 1979b; Brunskill et al., 1980). This comprehensive chemical, physical and biological study involved the collection of fifty bottom sediment grab samples and fourteen short cores (45-135 cm in length).

Prior to the recent Lake Winnipeg Project, no published geophysical surveys and only a few long cores have been taken. This limits the interpretation of the subsurface geology of Lake Winnipeg, including the structure of the basin and its long-term evolution, to extrapolations from land-based studies. Due to the need for enhanced understanding of the regional geological history a multidisciplinary offshore survey of Lake Winnipeg was proposed by the Geological survey of Canada (GSC) and Manitoba Energy and Mines in 1993.

The Lake Winnipeg Project (Phase I)

The Lake Winnipeg Project (Phase I) was carried out with the financial support from Manitoba Hydro, the Manitoba Sustainable Development Innovations Fund (MSDIF) and the GSC, with links established to ongoing research programs at the Freshwater Institute (Winnipeg) and several universities (Todd, 1996). Manitoba Hydro and the

MSDIF, both of which committed funds equivalent to 20 % of the total operating cost, sponsored the project largely due to their interest in shoreline erosion. Since 1976, Manitoba Hydro has been licenced to regulate lake levels for the purpose of energy generation (Raban, 1995). As a result, the corporation is interested in the history of shoreline erosion, especially around the highly developed South Basin.

In August 1994, the GSC cruise, designated Namao 94-900, proceeded aboard the Canadian Coast Guard Ship (CCGS) Namao. The cruise began with a northbound geophysical survey using sidescan sonar to image lakebed morphology and multi-channel and high resolution seismic reflection to obtain a subbottom profile; air and water sampling were undertaken concurrently with the geophysical survey (Todd, 1996). The southbound phase comprised the collection of sediment and limnological samples. Sediment sampling included thirteen gravity or piston cores, ten box cores and 31 Eckman dredge sites. A summary of sample locations is presented in Appendix 1-1. Limnological measurements recorded air and surface-water temperature, turbidity and conductivity-temperature-depth profiles. The offshore work was complemented by a comprehensive survey of the Lake Winnipeg shoreline in September, 1994 (Forbes and Frobel, 1996).

Two major questions were addressed by phase one of the Lake Winnipeg Project:

1. What is the structure of the Lake Winnipeg Basin? As alluded to earlier, very little is known about the subsurface geology of the lake basin.
2. Are recent sedimentary processes in Lake Winnipeg anthropogenically driven or are they the result of long-term geologic trends? An important factor is lake level, which, over geological time, can change dramatically in response to climatic change as well as isostatic uplift or tilting.

Objectives of this Study

This study comprises two areas of research. The first is to determine the thecamoebian distribution in Holocene sediments from Lake Winnipeg. Thecamoebians are

an informal group of testate protozoans commonly found in freshwater environments. Studies have shown that thecamoebian assemblages may vary throughout a lake's history; however, ecological controls have only been established for a small number of species. Thus, the multidisciplinary nature of the Lake Winnipeg Project has the potential to significantly add to our understanding of the environmental requirements of thecamoebians.

The objectives of this part of the study were three-fold:

1. to provide a detailed taxonomic account of the thecamoebian fauna, documenting both spatial and temporal variations;
2. to identify the environmental factors that influence the distribution;
3. utilization of faunal data to interpret lake history.

The second area of research involves determining the isotopic composition of common lead in Holocene sediments of Lake Winnipeg. There are four naturally occurring common Pb isotopes: ^{204}Pb , ^{206}Pb , ^{207}Pb and ^{208}Pb , of which only ^{204}Pb is non-radiogenic; the other three isotopes are daughter products of decay of U and Th (Faure, 1986).

Lead isotopes are not measurably fractionated by surficial physical, chemical or biological processes, thus lead in lake sediments retains the isotopic composition of its source material. Therefore, there is a potential to identify the natural and anthropogenic sources of lead by examining the isotopic composition.

The objectives of the lead work were three-fold:

1. to document spatial, temporal and compositional variations in the isotopic signatures of lead in Holocene sediments from Lake Winnipeg;
2. to identify the natural and anthropogenic sources from which the lead was derived and recognize changes in source through time;
3. to provide supporting evidence for the interpretation of lake history.

Original Contribution

This thesis consists of six chapters. The main scientific contributions are in chapters 3 to 5, which are in press, or submitted or will be submitted for publication. Each of these chapters is self-contained, with an abstract, introduction, discussion and conclusions. Tables and figures are presented at the end of each chapter. References have been compiled into a single list at the end of the thesis. Chapters 1 and 2 provide introductory and background information and chapter 6 presents the conclusions of this study as a whole.

All sediment cores were acquired by the shipboard scientists and crew of the GSC cruise Namao 94-900. Logging and subsampling of piston/gravity cores were completed by the staff of the GSC Dartmouth core facility and a group of the research scientists involved in the project, including S.M. Burbidge and C.J. Schröder-Adams. Box core samples were collected from material stored at the Freshwater Institute in Winnipeg, by S.M. Burbidge and C.J. Schröder-Adams.

All thecamoebian work, including sample preparation, qualitative and quantitative analyses and SEM work, was done by S.M. Burbidge. Sample preparation and mass spectrometry for lead analyses was performed by S.M. Burbidge with the assistance of Brian Cousens and John Blenkinsop. The chemical procedure for sequential extraction of lead fractions from the lake sediments was designed by Brian Cousens and John Blenkinsop.

Co-authored papers were written and revised by S.M. Burbidge and submitted to co-authors for critical review and discussion. The co-authors and current status of the papers contained in this thesis are as follows:

Chapter 3:

Burbidge, S.M., and Schröder-Adams, C.J., SUBMITTED. Holocene Thecamoebians of Lake Winnipeg, Manitoba, Canada. *Journal of Paleontology*.

Chapter 4:

Burbidge, S.M., and Schröder-Adams, C.J., IN PRESS. Thecamoebians in Lake Winnipeg: a tool for Holocene paleolimnology. *Journal of Paleolimnology*.

Chapter 5:

Burbidge, S.M., Blenkinsop, J. and Cousens, B., IN PREP. Sources of lead in Holocene Lake Winnipeg sediments: evidence from stable lead isotopic abundances.

CHAPTER 2.

LAKE WINNIPEG: PAST AND PRESENT

Lake Winnipeg is an integral part of the Nelson River drainage basin which extends from the Rocky Mountains to Hudson Bay (Figure 2-1). It is the largest of a group of lakes, including Lake Winnipegosis and Lake Manitoba, which are remnants of post-glacial Lake Agassiz. The water budget of Lake Winnipeg is supported by inflows from four major river systems: the Winnipeg River (mean monthly flow of $771 \text{ m}^3 \text{ s}^{-1}$), Saskatchewan River (mean monthly flow of $667 \text{ m}^3 \text{ s}^{-1}$), Red River (mean monthly flow of $159 \text{ m}^3 \text{ s}^{-1}$), and Dauphin River (mean monthly flow of $57 \text{ m}^3 \text{ s}^{-1}$) and numerous other streams surrounding the lake (Lewis and Todd, 1996). Except for the Winnipeg River, these major rivers drain areas of urbanization and agricultural activity to the south and west of the lake. As a result the waters have high alkalinity, mineral and nutrient content (Kling, 1996). The Winnipeg River, which drains from the Superior Province, is characterized by low nutrient supply and alkalinity. Thus, due to the differences in water quality between the eastern and western sources the lake water is heterogeneous. Outflow from Lake Winnipeg is through the Nelson River at the north end of the lake.

A constriction referred to as The Narrows divides the lake into two basins, the large North Basin (approximately 240 km by 100 km) and smaller South Basin (approximately 90 km by 40 km) (Figure 2-1). These basins have relatively flat and shallow lakebeds with water depths averaging 9 m in the South Basin and 16 m in the North Basin (Canadian Hydrographic Service, 1981). In contrast The Narrows is characterized by an irregular lake bed with water depths reaching a maximum of 61m.

Geologic Setting

Lake Winnipeg is situated on the contact between the Precambrian Superior Province to the east and Paleozoic carbonate and siliciclastic rocks of the Williston Basin to the west (Figure 2-2). The Paleozoic rocks of the western shore are underlain by

westward-dipping Precambrian basement (Weber, 1996). Most of what is known about the subsurface structure and lithologies of these Precambrian rocks has been interpreted from aeromagnetic surveys and limited diamond drilling.

The Superior Province in the Lake Winnipeg area is dominated by east-west trending Archean greenstone/granitoid belts, and metasedimentary/gneissic and plutonic belts. The belt structure of the western Superior Province is the result of Late Archean (>2.7 Ga) convergence of island arcs, accreted basins and older granitoid basement (Williams et al., 1992). Based on mapped lithotectonic units and major shear/fault zones, the western Superior Province in Manitoba is divided into nine subprovinces. Northwest of Lake Winnipeg these subprovinces are truncated by the northeast-trending Thompson Belt, which is part of the Churchill-Superior Boundary zone that resulted from the collision of two major Precambrian terranes, the Superior and Churchill Provinces 1.8 Ga ago (Weber, 1990).

Previously it was believed that Paleozoic strata pinched out against the Precambrian rock along a contact which ran parallel to the eastern margin of the lake. This was based on extrapolation of the regional, estimated thickness of Lower Paleozoic strata toward the eastern shoreline. Seismostratigraphic analysis of the Lake Winnipeg Basin, however, revealed that the Paleozoic-Precambrian boundary is as much as 60 km west of its previously estimated location and characterized by notable geologic structures (Bezys, 1996). In the North Basin there is evidence of faulting at the Precambrian-Paleozoic contact; Paleozoic faulting may have been due to the reactivation of an Archean structure (Weber, 1996). In the South Basin, the Paleozoic strata terminate at a prominent subsurface escarpment (Todd and Lewis, 1996).

The Paleozoic rocks, consisting of Ordovician- to Mississippian-age strata, range in thickness from zero at the Precambrian-Paleozoic boundary, to approximately 100 m on the western shore of Lake Winnipeg to almost 1300 m in the southwestern corner of Manitoba, and dip gently to the southwest (Bezys, 1996). Along the west shore of Lake Winnipeg,

outcrops and subcrops of Ordovician strata consist of arenaceous mudstone and siltstone overlying sandstone both forming the Winnipeg Formation. This formation is overlain by dolomite and limestone grading into argillaceous dolomite and intraformational breccia beds of the Red River Formation and massive dolomite of Stony Mountain Formation (Figure 2-3). Farther to the southwest these rocks are overlain by dolomite of the Silurian Interlake Group.

Trends in the isopachs of Lower Paleozoic strata suggest uplift and truncation of the eastern boundary of the Williston Basin in the Lake Winnipeg area; thus, the Lower Paleozoic sequence of the basin extended much further east than is observed today (Bezys, 1996; Norford et al., 1994). Post-Silurian reactivation of basement faults or lineaments may have been responsible for differential uplift and erosion and emergence of the Precambrian Shield as a geographic feature.

Mesozoic rocks, predominantly shales with some sandstones and red beds, unconformably overlie Paleozoic rocks in southwest Manitoba (Figures 2-2 and 2-3). The unconformity at the base of the Mesozoic has considerable relief, with erosional valleys and karst topography developed in numerous places on the underlying Paleozoic surface (Teller and Bluemle, 1983). The eastern extent of the Mesozoic is irregular, and Jurassic strata overlie rocks ranging in age from Precambrian to Mississippian; Mesozoic rocks in the West Hawk Lake meteorite impact crater east of Winnipeg, however, suggest that these rocks may have extended well to the east of their present limit (Dence et al., 1968).

In southwestern Manitoba, Tertiary shale and lignite overlie Cretaceous strata (Figure 2-3); these mainly Paleocene sediments are highly dissected and occur only as outliers along their eastern margin. The early and mid-Tertiary extent of these Paleocene sediments is not known, but it is likely they once covered much of the area at least as far east as the Manitoba Escarpment (Teller and Bluemle, 1983).

Quaternary Basin History

The area is covered by Quaternary sediments deposited by southwestward-flowing ice of the Wisconsinian continental ice sheet. Paleozoic strata to the west of Lake Winnipeg have generated thick accumulations of drift which include large glacial geomorphological features such as drumlinoid ridges and moraines (Nielsen and Thorleifson, 1996). Till of the Interlake (the area between Lake Winnipeg and lakes Manitoba and Winnipegosis) forms an almost continuous sheet of compact, fissile, silty, very calcareous material which contains an abundant gravel fraction. In marked contrast, Precambrian rocks to the east and north have generated little sediment (Klassen, 1967), resulting in extensive bedrock outcrop. Till forms a thin and discontinuous veneer, draped over the bedrock surface; it occurs as a loose, sandy diamicton derived almost exclusively by the erosion of local Precambrian rocks. The shield to the north of the lake is extensively drift covered due to Paleozoic sediment derived from the Hudson Bay Lowland. Till is not common within the Lake Winnipeg Basin, but two formerly unrecognized major moraines, the Pearson Reef Moraine in the South Basin and the George Island Moraine in the North Basin, were identified (Todd and Lewis, 1996).

The till surface in many places shows evidence of glaciolacustrine influence resulting from the formation of glacial Lake Agassiz. Topographic highs are commonly capped by boulder lags formed by wave action during the regression of Lake Agassiz (Henderson, 1994), while low-lying areas are generally covered by fine glaciolacustrine sediments. Silt and clay rhythmites deposited in Lake Agassiz are extensive to the south and north of the lake. In the southern Interlake, glaciolacustrine sediments have been mixed with the underlying till by wind-driven icebergs which impinge on the lake bottom (Nielsen and Thorleifson, 1996). Within the Lake Winnipeg Basin, sediments consisting almost entirely of Lake Agassiz clay reach unexpected thicknesses of > 50 m in the South Basin and > 100 m in the North Basin (Todd and Lewis, 1996).

Since the onset of the Wisconsinian glaciation, the ice sheet had a complex history of advances and retreats; however, very little evidence remains of the early phases of ice movement. Striations on the east side of the lake indicate that the most recent ice flow was southwestward and southward (Henderson, 1994), while striations and drumlinoid ridges indicate a more complex sequence of southwestward, southward and finally southeastward ice flow in the Interlake. This southeastward flowing ice eventually converged with ice flowing southwestward from the shield, and advanced southward along the Red River Valley (Nielsen and Thorleifson, 1996).

After 11.5 ka B.P., the Red River Lobe had retreated north of the divide between the Hudson Bay and Mississippi River drainages; Lake Agassiz first formed as water was impounded in the Red River Valley against this retreating ice margin (Fenton et al., 1983). At its zenith, about 9.5 ka B.P., Lake Agassiz covered 350,000 km². The lake initially drained through the extreme southern end of the lake (Clayton, 1983) but as the ice retreated, outlets developed through the Superior basin to the east (Teller and Thorleifson, 1983). When the ice sheets had retreated as far north as the mouth of the Nelson River, approximately 7.5 ka B.P., access to Tyrrell Sea, a precursor to Hudson Bay, became available (Klassen, 1983). This resulted in a sudden drainage of the remaining part of Lake Agassiz, which left behind the ancestral forms of lakes Winnipeg, Manitoba and Winnipegosis.

During the various phases of Lake Agassiz several types of sedimentary deposits were formed, such as outwash plains, deltas and beaches. The ancient beaches of Lake Agassiz can be seen today as nearly parallel sand or gravel ridges or as wave-cut cliffs along carbonate bluffs. These beach ridges are higher to the northeast because of unequal glacial rebound (McMartin, 1996). There is also evidence that the coast of Hudson Bay continues to rise and that the Great Lakes continue to tilt in response to isostatic rebound. Gradients on individual beaches steepen to the north indicating there has been a higher tilt rate in the northern than in the southern part of the region. Careful examination of a time-

series of Lake Agassiz strandlines indicated that the rate of crustal tilting quickly declined as glacial retreat progressed (Lewis and Todd, 1996). Whether the rate of isostatic rebound continued to decline after the final drainage of Lake Agassiz is unknown.

The post-glacial tilting history of the region has important implications for the Lake Winnipeg basin. Tilting of the basin from post-Agassiz time until today, as indicated by Lake Agassiz standlines and the Great Lakes uplift history, suggests that Lake Winnipeg was initially a much smaller water body. During the earliest phase of Lake Winnipeg the water would have been confined to the North Basin but transgressed southward as the drainage threshold at the head of the Nelson River outlet rose more rapidly than other parts of the basin (Lewis and Todd, 1996).

Preliminary results from the Lake Winnipeg Project indicate that Lake Winnipeg has been undergoing gradual southward extension. Sediment cores in the central part of the South Basin contain fossiliferous peat layers which could only have been deposited at a previously existing shoreline. Basin modelling suggests the existence of independent central and southern basins prior to 2.5 ka B.P. These restricted “ponds” drained northward over threshold sills into the northern lake (Lewis and Todd, 1996).

The survey of shoreline geology documented erosional features around the southernmost South Basin beaches, indicating gradual transgression to the south as a result of tilting due to isostatic uplift of the Hudson Bay region. Evidence for differential rebound continuing today suggests that southward transgression persists and if this is the case, then shoreline erosion at the head of the South Basin is a natural process and not due to anthropogenic interference (Forbes and Frobel, 1996).

The regional tilting history of the Lake Winnipeg basin has also affected the lake catchment. Prior to mid-Holocene time (2.5-5.9 ka .B.P.) the Saskatchewan River bypassed Lake Winnipeg via the Minago River channel; however, isostatic uplift to the northeast allowed the river to breach the till barrier west of Grand Rapids and divert to its present course (McMartin, 1996). Superimposed on the effect of uplift is the influence of

changing inflow caused by climate change and the mid-Holocene diversion of the Saskatchewan River into Lake Winnipeg (Lewis and Todd, 1996).

Sediments of Lake Winnipeg

Thirteen gravity and piston cores, ranging in length from 2 m to 8 m, were obtained to sample the sediment in order to verify stratigraphy and to supply material for subsequent geological and paleontological analyses (Figure 2-4). Cores were recovered from both the North and South basins. In addition to the long cores, a series of ten box cores were collected for high-resolution study of recent sedimentation. Appendix 1-1 gives details of core locations.

Two sequences are recognized within the Holocene sediments (Figure 2-5): a thick Lake Agassiz sequence overlain by a thinner Lake Winnipeg sequence. In the North Basin, the lower sequence is characterized by two units of firm, brownish grey to olive grey, silty clay rhythmites topped by a unit of firm banded silty clay with occasional dropstones and grit in the basal section (Lewis and Todd, 1996). The two rhythmite units are differentiated by the thickness of the couplets: thin ($< 1\text{ cm}$) in the lower unit and mainly thick (1-5 cm) in the upper unit. This sequence is interpreted as deposits in glacial Lake Agassiz, with rhythmites resulting from seasonal variations. The upper banded clay is interpreted as representing deposition during late stages of Lake Agassiz, when the ice margin had retreated far to the north.

In the South Basin the Lake Agassiz sequence is very firm clay and is commonly orangish brown or brownish grey. The rhythmite units are characterized by beds of diffusely banded silty clay and dropstones. This is interpreted as glaciolacustrine sediment and ice-rafted debris, possibly disturbed by iceberg scour or glacial overriding (Lewis and Todd, 1996).

The Lake Winnipeg sequence overlies a regional erosional unconformity (Agassiz Unconformity). The sediments are characteristically soft, dark olive grey, silt-clay mud

with discontinuous bands of lighter grey mud and sand grains near the base. This sequence is the result of accumulation in modern Lake Winnipeg and is rarely more than 10 m thick.

Water column analyses

Thirty-three Eckman grab samples were collected from an array of evenly spaced target sites (Figure 2-6). At each of these locations, air and surface water temperature and Secchi disk measurements were taken (Table 2-1). Secchi disk measurements estimate the transparency of the water, which is influenced by the absorption characteristics both of the water and of its dissolved and particulate matter. Standard equipment and procedures were used in obtaining Secchi disk measurements.

In addition, temperature-depth profiles were determined at twenty-four of the thirty-three sites. Lake Winnipeg is unstratified in the summer as illustrated by largely vertical temperature-depth profiles (Figure 2-7). The upper horizontal parts of the profiles represent warm surface water which can be easily mixed into underlying water by windy conditions (e.g. sample 9). Most of the water column is represented by the near parts section of the profiles. On the west side of the North Basin (samples 1, 3, and 6) the profiles show a slightly warmer subsurface layer which is attributed to inflow from the Saskatchewan River. The horizontal bottom parts of the profiles record the cooler temperatures below the sediment-water interface. The summer water temperatures recorded for Lake Winnipeg were 16.5° - 17.5°C in the North Basin, approximately 19°C in The Narrows and 19.5° - 20.5°C in the South Basin.

Chronology

A number of radiometric and AMS dates were attempted on material from Lake Winnipeg. A series of bulk sediment samples were dated, however, the resulting ages were rejected because the sediment-water interface did not have an age of zero.

Inconsistencies are probably due to the presence of “old” carbon derived from Cretaceous and other rocks (Lewis and Todd, 1996). AMS and radiometric dating of bulk lacustrine sediments is not advisable.

An exceptionally well preserved bullrush achene from a peat layer immediately above the Agassiz Unconformity in Core 122a (South Basin) yielded the only reliable AMS ^{14}C date of 4040 ± 70 B.P. (Vance, 1996). The plant macrofossil assemblage and sediment characteristics clearly indicate a shoreline location for the sediments in Core 122a at that time. Consolidated Lake Agassiz rhythmites directly overlain by the basal peat layer of the Lake Winnipeg sequence suggest a hiatus between the sequences.

King and Gibson (written comm.) have developed age models for the Lake Winnipeg sediments of Core 103 (North Basin) and Core 122a (South Basin) using geomagnetic secular variation (SV). Lake Winnipeg SV curves were correlated with SV curves from locations in Minnesota and the Northeastern United States which had age control based on varves and radiocarbon dates. The age model derived from SV is consistent with the single radiocarbon date from Core 122a. Figure 2-8 presents the SV age models for Cores 103 and 122a. These model ages indicate an average sedimentation rate of $0.98 \text{ mm year}^{-1}$ in the North Basin and 1.2 mm year^{-1} in the South Basin.

Table 2-1: Temperature and Secchi depth measurements from the grab sampling survey.

Site	Basin	Depth (m)	Air Temperature (°C)	Water Temperature (°C)	Secchi Depth (m)
1	North	13.9	18.8	19.1	2.5
2	North	14.3	19.8	19.0	3.3
3	North	12.4	19.8	18.9	3.0
4	North	12.8	19.7	18.4	4.0
5	North	14.8	17.9	17.2	2.4
6	North	14.6	17.8	20.2	3.5
7	North	15.0	18.4	18.5	2.9
8	North	15.3	20.3	17.5	2.5
9	North	14.1	18.0	17.2	1.7
10	North	16.3	19.1	17.8	2.2
25	Narrows	9.3	18.8	18.8	1.0
28	Narrows	9.6	19.3	19.0	1.0
29	Narrows	10.8	20.8	20.1	0.8
30	Narrows	12.4	18.4	20.8	0.8
31	Narrows	14.3	19.8	20.0	0.8
32	Narrows	8.8	23.8	20.8	0.6
33	Narrows	12.2	21.9	21.9	0.6
34	South	11.9	19.2	20.2	0.6
35	South	9.9	18.3	19.5	0.8
36	South	10.0	16.8	19.4	1.1
37	South	10.4	18.3	18.6	1.0
38	South	7.9	17.0	18.5	0.7
39	South	7.9	15.2	18.0	0.7
40	South	4.6	16.7	18.1	0.6
41	South	10.7	16.0	19.2	0.6
42	South	9.7	17.1	19.6	1.0
43	South	8.4	17.1	19.7	0.8
44	South	9.8	18.1	19.7	1.3
45	South	10.1	15.4	18.0	0.8
46	South	9.6	19.0	19.8	1.1
47	South	11.9	16.1	18.6	1.0
49	South	8.5	13.5	16.9	0.4
50	South	7.0	12.6	17.1	0.3

Figure 2-1: Simplified map showing the location of Lake Winnipeg (shaded) and the major rivers of the catchment.

Figure 2-2: Geological map of Manitoba (after Teller and Bluemle, 1983).

Legend

Tertiary

Cretaceous

Jurassic

Devonian

Silurian

Ordovician

Precambrian

----- Maximum extent of Lake Agassiz

Figure 2-3: Regional structural cross section showing Paleozoic to Cenozoic formations in southern Manitoba (modified after Bezys, 1996).

A'

A

Figure 2-4: Location of piston/gravity core and box core sites (modified after Todd, 1996).

Figure 2-5: Generalized lithology of cores of Lake Winnipeg (modified after Lewis and Todd, 1996).

South Basin

North Basin

Figure 2-6: Location of sampling survey stations for Eckman grab samples and water column analyses (modified after Todd, 1996).

Figure 2-7: August temperature-depth profiles for selected locations in Lake Winnipeg (modified after Todd, 1996).

Figure 2-8: Secular age models for Core 103 in the North Basin and Core 122a in the South Basin (King and Gibson, written comm.).

CHAPTER 3.
HOLOCENE THECAMOEBIANS OF
LAKE WINNIPEG, MANITOBA, CANADA

ABSTRACT

This paper is a detailed taxonomic account of the thecamoebian fauna of Lake Winnipeg, documenting species diversity and intraspecific variability. Since thecamoebians are non-interbreeding, there is no objective way to confirm the validity of a specific group. The identification process is further complicated by the wide range of intra- and interspecific variability exhibited by this group. The term strain is introduced for designating infraspecific variations in thecamoebian test morphology. These strains were assigned previously published names according to the original designation and/or commonly accepted synonymy of the taxa. Twenty-four species of thecamoebians from eight families are identified from Holocene sediments of Lake Winnipeg. Five species, Centropyxis aculeata, Diffugia protaeiformis, Diffugia fragosa, Diffugia oblonga, and Diffugia urceolata, are further subdivided into morphologically distinct strains. Diagnoses are included to distinguish between strains of a given species group.

Most fossilized lacustrine thecamoebians have xenogenous tests which consist of foreign material (mineral grains, diatoms, etc.) cemented to an internal organic pellicule. Thecamoebians are nonselective and the nature of the xenosomes appears to be controlled by the composition of the substrate. Lake Winnipeg specimens are generally small in size and use only mineral xenosomes to compose their tests; no diatomaceous xenosomes were observed.

INTRODUCTION

Thecamoebians are an informal polyphyletic group of testate protozoans also referred to as agglutinated rhizopods or testate amoebae. This group, belonging to the subphylum Sarcodina, includes taxa from the classes Rhizopodea and Reticularia (Loeblich and Tappan, 1964). Only a small part of the class Rhizopodea, order Arcellinida are commonly fossilized, thus a large portion of the taxa included in thecamoebians are paleontologically insignificant (Medioli and Scott, 1983).

This collection of rather diverse organisms shares three major features: a) an amoeboid cell, b) pseudopods of variable nature, and c) a simple sac-like or cap-like test. Thecamoebians are found in all types of freshwater bodies as well as a variety of moist environments (mosses, damp soils, tree bark); only a few seem to tolerate brackish conditions. Their known stratigraphic range extends to the Carboniferous (Thibaudau et al., 1987).

Most of the early literature (e.g., Leidy, 1879; Penard, 1902; Cash and Hopkinson, 1909) dealt with the taxonomy of living lacustrine species. In more recent work, attention has turned to the classification of species from mosses and soil (e.g. Heal, 1962; Bonnet, 1964; Nair and Mukherjee, 1968). Most of these studies were biological in nature with fossilized material largely being ignored even though thecamoebians are often conspicuous in Holocene lacustrine sediments.

Because their tests resist dissolution in low pH environments, unlike calcareous organisms such as mollusks and ostracods, thecamoebians are commonly preserved in lacustrine (Medioli and Scott, 1988). Although these attributes suggest thecamoebians would be good paleolimnologic indicators, the paucity of ecologically based studies means their ecologic requirements are poorly understood. Ecological controls have, as yet, only been established for a small number of species. A few of the more recent studies have made correlations to parameters such as organic material or chemical pollutants in the sediment, trophic grade of the lake, climatic conditions, or rate of clastic input (e.g.,

Collins et al., 1990; McCarthy et al., 1995; Asioli et al., 1996). These studies have concentrated on small lakes. With the exception of Scott and Medioli's (1983) work on Lake Erie, little thecamoebian research has been done on large lakes such as the Canadian Great Lakes or Lake Winnipeg.

Despite Lake Winnipeg being the eleventh largest lake in the world and being vital to Manitoba's economy for hydroelectricity, fisheries and recreation, little scientific investigation has been carried out. The Freshwater Institute of Fisheries and Oceans Canada completed a limnological survey in 1969 which included the collection of bottom sediment samples and short cores. However no thecamoebian analysis was performed on these samples. A more recent study of Lake Winnipeg was proposed in 1993 to study the nature of sedimentary deposits and the geological history of Lake Winnipeg and its predecessor, Lake Agassiz. This comprehensive approach included a geophysical survey (seismic reflection and sidescan sonar), sediment sampling (piston cores, box cores and grab samples), water column analyses (water temperature, transparency and conductivity), plankton sampling and water sampling. Because of its multidisciplinary nature, the Lake Winnipeg Project has the potential to significantly add to our knowledge of thecamoebians. A quantitative and qualitative analysis of Holocene thecamoebians including their paleolimnological significance was presented by Burbidge and Schröder-Adams, (in press). This paper is a detailed taxonomic account of the thecamoebian fauna of Lake Winnipeg to document species diversity and intraspecific variability.

GENERAL CHARACTERISTICS OF THECAMOEBIANS

The test. -- Thecamoebians have a unilocular shell or test with a simple aperture or opening for the extrusion of pseudopods. Tests can be secreted by the organism (autogenous tests) or built by agglutinating foreign particles (xenogenous tests) in organic cement (Medioli and Scott, 1988).

Autogenous tests are of three basic types: proteinaceous, siliceous and calcareous.

The only proteinaceous tests which are likely to be preserved in lacustrine environments are those in which the test wall is constructed of alveoli or building blocks. Often the alveoli contain inorganic substances such as amorphous manganese or iron which are most likely utilized to strengthen the test wall (Ogden and Hedley, 1980). Some species of Arcella and Centropyxis are characterized by this type of test construction. A second type of proteinaceous test consists of one or more continuous layers of mucoprotein (Joyon and Charret, 1962; Griffin, 1972).

Siliceous tests are constructed of plates or rods which are secreted in the cytoplasm prior to cell division (Ogden and Hedley, 1980). Some thecamoebians (e.g. Euglypha) are composed entirely of self-secreted particles (idiosomes) arranged in a distinctive pattern; others contain variable amounts of foreign material mixed with the autogenous particles (e.g. Lesquereusia). These mixed tests tend to fossilize in lacustrine environments, whereas the ones made entirely of autogenous silica rarely do (Medioli and Scott, 1988).

Calcareous autogenous tests are composed of overlapping shell plates or a solid layer of crystalline calcite. They are of minor paleolimnological significance because fossilization is extremely rare (Medioli and Scott, 1988).

Almost all fossilized lacustrine thecamoebians have xenogenous tests. These can be divided into two groups. The first group contains most of the family Diffugiidae; these possess tests characterized by foreign material cemented to an internal organic pellicule (Deflandre, 1953). Thecamoebians are nonselective and the nature of the xenosomes appears to be almost entirely controlled by the composition of the substrate (Medioli et al., 1987). They include mineral grains (calcareous or siliceous) and/or diatom frustules as well as more exotic materials such as wood pulp, debris of other skeletons and a variety of unidentified particles (Medioli and Scott, 1988).

The second type of agglutinated tests occurs in the genera Heleopera and Nebela (Ogden and Hedley, 1980). It is commonly recognized that these genera do not make their

own idiosomes but agglutinate those of the thecamoebians on which they prey. This may produce a siliceous test similar in appearance to euglyphaceans. The pattern of “pseudo-idiosomes” is usually diagnostic for different species.

The general morphology of the thecamoebian tests can be divided into two broad categories: the cap-shaped group (e.g. Centropyxis), with the invaginated aperture on the flattened ventral side; and the flask-shaped group (e.g. Diffflugia) with the aperture located at the tapered end of the test. A wide range of variability is observed within these two broad groups. A few forms (e.g. Lagenodifflugia) possess an apparent second chamber because the neck is separated from the rest of the test by an internal diaphragm.

Thecamoebian tests range in size from smaller than 30 μm to larger than 300 μm in length but most lacustrine species commonly range from 60 μm to 200 μm .

The living organism. -- Two features characteristic of all thecamoebians are the amoeboid cell encased in the test and the pseudopods extending through the aperture. Most of what is known about the cytoplasm is derived from the study of transparent autogenous species; not much is known about the cytoplasm of the opaque thecamoebians which represent the vast majority of the known fossilized forms.

The pseudopods are flowing extensions of cytoplasm protruding through the aperture. The structure of the pseudopods is generally accepted as the basis for rhizopod, including thecamoebian, macrotaxonomy. Three types of thecamoebian pseudopods are commonly recognized: lobose (finger-like, usually with rounded distal ends), filose (comparatively thin, pointed and often branching), and reticulose (fine, branching and anastomosed strands) (Deflandre, 1953).

It is commonly assumed that filose and lobose pseudopods are used strictly for locomotion and do not have digestive functions. A number of lobose species have been observed feeding and in all cases the organisms moved the food inside the test and, presumably, digested it in the endoplasm (Stump, 1935; Hoogenraad and DeGroot, 1941).

Small lacustrine thecamoebians feed mainly on bacteria, fungi, and algae (Ogden and Hedley, 1980). The larger species also appear to prey upon other protozoans, such as testate and naked amoebae (Mast and Root, 1916). Other species have developed a parasitic relationship in which they consume the cell contents of certain filamentous green algae (Stump, 1935; Hoogenraad and Groot, 1941; Medioli et al., 1987).

Thecamoebian reproduction is almost exclusively by asexual binary fission in which the parent is replicated to form an identical daughter (Ogden and Hedley, 1980). Replication can occur every two to eleven days (Lousier, 1974). Rare cases of sexuality have been documented (Valkanov, 1966).

After asexual reproduction the test apparently does not grow (Penard, 1902). The size of the individual is probably controlled to a large degree by the volume of cytoplasm available in the parent test at the time of fission; this is largely influenced by the availability of food and the length of the feeding period preceding reproduction (Medioli et al., 1990).

Encystment occurs in a large number of thecamoebian species as a means of rest, dormancy or defense (Ogden and Hedley, 1980). Cysts are capable of withstanding extreme environmental conditions such as desiccation, freezing or lack of food. Encystment capability allows thecamoebians to be readily transported and distributed, while still alive, over long distances by a variety of agents; thus thecamoebians have a worldwide distribution.

LOCATION

Lake Winnipeg is situated over the Precambrian-Paleozoic contact between the Canadian Shield and the Williston Basin. It covers over 24,000 km² and is an integral part of the Nelson River drainage basin, which extends from the Rocky Mountains to Hudson Bay. A constriction referred to as The Narrows divides the lake into two basins, the large North Basin and smaller South Basin (Figure 3-1). These basins have relatively flat and

shallow lakebeds with water depths averaging 9 m in the South Basin and 16 m in the North Basin (Canadian Hydrographic Service, 1981).

The water budget of Lake Winnipeg is supported by inflows from four major river systems (the Winnipeg, Saskatchewan, Red-Assiniboine and Dauphin rivers) and numerous other streams surrounding the lake (Lewis and Todd, 1996) (Figure 3-1). Except for the Winnipeg River, these major rivers drain areas of urbanization and agricultural activity to the south and west. As a result the waters have high alkalinity, mineral and nutrient content (Kling, 1996). The Winnipeg River, which drains from the Superior Province, is characterized by low nutrient supply and alkalinity. Temperature profiles measured in late summer reveal Lake Winnipeg is unstratified.

Two Holocene sedimentary sequences separated by an erosional unconformity are recognized in the Lake Winnipeg basin: the lower Lake Agassiz sequence and the overlying Lake Winnipeg sequence (Lewis and Todd, 1996). In the North Basin, the Lake Agassiz sequence is characterized by intervals of silty clay rhythmites topped by a firm unit of banded silty clay. This sequence differs slightly in the South Basin where it consists of stiff to hard diffusely banded silty clay and silty clay rhythmites. Some of the sediments are orange-brown or brownish grey in colour. This sequence is devoid of thecamoebians as well as diatoms and tintinids (Burbidge and Schröder-Adams, in press).

The Lake Winnipeg sequence comprises soft, dark olive grey, silt-clay mud (Lewis and Todd, 1996). The basal erosional contact is commonly marked by sand grains and occasionally shells and plant fragments. The lowermost interval of the Lake Winnipeg sequence often displays faint, discontinuous bands of lighter grey mud. This sequence contains a rich assemblage of thecamoebians, diatoms and tintinids (Burbidge and Schröder-Adams, in press).

MATERIALS AND METHODS

Phase one of the Lake Winnipeg Project, designated Namao 94-900, proceeded aboard the Canadian Coast Guard Ship Namao in August 1994. Of the material collected, nine gravity or piston cores were selected for qualitative and quantitative analyses of thecamoebians (Figure 3-1). Samples were analyzed at 40 cm intervals in all cores (except Core 105) beginning with the uppermost sample (5 cm) and proceeding downcore to include at least one sample from the Lake Agassiz sequence. Core 105 was sampled every 20 cm because the Lake Winnipeg sequence is thin.

In the laboratory, samples were weighed to determine approximate sample size. Since drying can cause disaggregation of thecamoebian tests, materials were not dried prior to weighing. Samples were soaked in water and soda ash for 30 minutes to aid breakdown of the consolidated mud. Each sample was then gently wet-sieved through a no. 325 mesh (0.044 mm) to remove the clays. The soaking and washing process was repeated if necessary to completely remove all mud. The washed residues were then immersed in ethanol (95%) and water for storage and examination.

Analysis was performed using a combination of transmitted and reflected light under a binocular dissecting microscope. Specimens were extracted from the ethanol-water solution with a very fine brush and mounted on micropaleontological slides coated with Gum Tragacanth. For SEM work a small disk of photographic film (emulsion side up) was glued to a standard aluminum plug; the mounted specimens were transferred to the plug and held there by the film emulsion. Prepared stubs were evenly coated with gold using a standard sputter coating device, and examined in a JEOL JSM 6400 Scanning Electron Microscope operating at between 3 and 10 kV. The results were digitally recorded using the Link System Image grabber.

TAXONOMIC APPROACH

Since thecamoebians are virtually non-interbreeding organisms, taxonomic identification at the species level is arbitrary (Medioli and Scott, 1983). There is no objective way to confirm the validity of a specific group. The identification process is further complicated by the wide range of intra- and interspecific variability exhibited by this group. The two extreme viewpoints are: Wallich's (1864) opinion that all thecamoebians belong to the same species, or the opinion that every morphological variation represents a genuine species. A detailed discussion of the species problem in thecamoebians is presented by Medioli and Scott (1983) and Medioli et al. (1990). A simple solution to the problem does not exist but practical considerations dictate that a sensible compromise be found.

For the purposes of this study specimens were first sorted into the widely variable species groups of Medioli and Scott (1983). Within some of the species groups the specimens exhibited an intergradational series; these groups were identified as species. Meanwhile, other species groups exhibited an uneven distribution of specimens with clusters of particular morphologies conspicuous over the background intergradation. These morphologically similar concentrations are referred to as strains of the species group. Any approach in identifying fossil material has to remain subjective.

The term strain is used to distinguish asexually produced variants in viruses and bacteria, and it is legitimate for designating infraspecific variations in thecamoebian test morphology (Medioli, 1997). Whenever possible, previously published names were used to facilitate comparison between studies. Each strain is assigned to a species group according to the original designation of the taxa and/or commonly accepted synonymy found in the current literature. For example, Diffflugia oblonga "oblonga", Diffflugia oblonga "lacustris", Diffflugia oblonga "lanceolata" and Diffflugia oblonga "linearis" are four distinct strains of the species Diffflugia oblonga. Recognition of these strains is important; the abundance or dominance of a particular strain may well be in response to

distinctive environmental conditions (Asioli et al., 1996). Therefore, if thecamoebians are to be used as paleolimnological tools, the identification of ecologically influenced strains within species is vital. Environmental preferences of some species and strains documented in this paper are discussed in Burbidge and Schröder-Adams (in press).

GENERAL OBSERVATIONS

Lake Winnipeg specimens use only mineral xenosomes to compose their tests. No diatomaceous xenosomes were observed which may be the result of an ample supply of suitable mineral xenosomes in the substrate.

Tests of Lake Winnipeg thecamoebians are generally small; usually they are near the lower size range limit. The size of the test is the result of the food availability and the feeding period prior to asexual fission (Medioli et al., 1990). If thecamoebians replicate often without extended feeding periods between generations, the test will most likely be small; thus it appears that Lake Winnipeg is a very productive lake.

SYSTEMATIC PALEONTOLOGY

The suprageneric classification and generic descriptions follow Medioli and Scott (1988), Medioli et al. (1987), and Loeblich and Tappan (1964). Synonymies include the initial reference and references which document the history of specific taxonomic placement. Diagnoses are included only to help distinguish between strains of a given species group. Strains are designated by quotation marks around non-italicized descriptive latinized names or letters.

Subphylum SARCODINA Schmarda, 1871

Class RHIZOPODEA von Siebold, 1845

Subclass LOBOSA Carpenter, 1861

Order ARCELLINIDA Kent, 1880

Superfamily ARCELLACEA Ehrenberg, 1830

Family ARCELLIDAE Ehrenberg, 1830

Genus *Arcella* Ehrenberg, 1830

Type species. -- *Arcella vulgaris* Ehrenberg 1830, p.40.

Description. -- Test composed of chitinoid membrane, transparent, punctate or minutely cancellate, rarely spinose, hemispherical; central recurved circular to crenulate aperture in circular base; young tests hyaline, adult brown; pseudopodia few, lobose. (Brackish to fresh water.)

Arcella vulgaris Ehrenberg, 1830

Figure 3-2.1

Arcella vulgaris EHRENBURG 1830, p. 40, pl. 1, fig. 6.

Description. -- Test pale to dark brown, circular in dorsal view and hemispherical in cross-section, often having a slightly expanded basal collar; relatively smooth surface with numerous fine pores; aperture central, invaginated, circular, and bordered by a small lip; diameter of test 65 - 80 μm , height approximately 40 μm and diameter of aperture 20 - 25 μm .

Remarks. -- This species is relatively rare in Lake Winnipeg. The tests are smaller than those reported by Ogden and Hedley (1980) but fall within the lower sizes of the wide range reported by Leidy (1879). Their small size makes them difficult to discern from other small disc-shaped species such as *Oopyxis* sp. and *Phryganella acropodia*. *Arcella vulgaris* however, has a small central aperture while *Oopyxis* sp. is characterized by a sub-terminal aperture (Figure 3-7.11) and *Phryganella acropodia* a large aperture (Figure 3-8.1 - 3-8.3).

Family CENTROPYXIDIDAE Deflandre, 1953

Genus *Centropyxis* Stein, 1859

Type species. -- Arcella aculeata Ehrenberg, 1832, p. 91.

Description. -- Test chitinous, colourless to brown, with or without agglutinated xenosomes; discoid to oval with flattened ventral side, posterior edge maybe ornamented by one or more spines; surface smooth or irregular depending upon secondary agglutination; aperture ventral, eccentric anteriorly, circular or ovate, invaginated; pseudopodia digitate. (Slightly brackish to fresh water.)

Centropyxis aculeata (Ehrenberg 1832)

Strain: *Centropyxis aculeata* “aculeata”

Figure 3-2.2 - 3-2.5

Arcella aculeata EHRENBURG, 1830, p. 60, nomen nudum.; EHRENBURG, 1832, p. 91;

EHRENBURG, 1838, p. 133, pl. 9, figs. 6a-c.

Centropyxis aculeata (Ehrenberg). STEIN, 1859, p. 43.

Echinopyxis aculeata (Ehrenberg). CLAPARÈDE and LACHMANN, 1859, p. 447.

Diagnosis. -- A strain of Centropyxis aculeata with a relatively flat circular test bordered by lateral spines.

Description. -- Test colourless to yellow or brown, ovoid or circular and usually with four or more lateral spines; spherical and tapering towards the aperture in lateral view; surface rough, often covered with fine to medium silt grains except for smooth region around aperture; aperture invaginated, circular to oval and sub-terminal; test diameter 80 - 120 µm, height approximately 50 µm and aperture diameter 30 - 50 µm.

Remarks. -- Centropyxis aculeata “aculeata” is the most abundant of the Centropyxis aculeata strains. Variation observed in this strain is limited to the number of spines and the coarseness of the xenosomes. In Lake Winnipeg, xenosomes are exclusively mineral particles with diatom frustules never being agglutinated though diatom xenosomes are commonly observed elsewhere (e.g. Medioli and Scott, 1983; Ogden and Hedley, 1980). The lack of diatomaceous xenosomes is unusual since Lake Winnipeg is considered to be a

diatom-bluegreen algae lake (Kling, 1996). Perhaps the available frustules are too large to be agglutinated. The tests are small and fragile and are found in size ranges consistent with Leidy (1879) but smaller than those reported by Ogden and Hedley (1980).

Strain: *Centropyxis aculeata* “discoides”

Figure 3-2.6 - 3-2.7

Arcella discoides EHRENBURG, 1843a, p. 139; EHRENBURG, 1872, p. 259, pl. 3, fig. 1;
LEIDY, 1879, p. 173, pl. 28, figs. 14-38.

Centropyxis aculeata var. discoides PENARD, 1890, p. 150, pl. 5, figs. 38-41; WAILES,
1919, p. 34, pl. 61, figs. 1-2.

Centropyxis discoides Penard. OGDEN and HEDLEY, 1980, p. 54, pl. 16.

Diagnosis. -- Specimens of Centropyxis aculeata characterized by a brown, circular, spineless test with a subcentral aperture.

Description. -- Test brown, circular, discoid in lateral view, depressed; apertural side smooth, aboral side rough due to incorporation of fine silt grains; aperture invaginated, circular, subcentral; test diameter 100 - 150 μm , height 30 - 50 μm , aperture diameter 40 - 70 μm .

Remarks. -- This strain of Centropyxis aculeata is the largest of the three strains it is, however, still smaller than reported elsewhere (e.g. Ogden and Hedley, 1980). Variation occurs most frequently in the size and eccentricity of the aperture.

Penard (1890) assigned the variety discoides to Centropyxis aculeata. Whether Penard intended to designate a new taxon or a new combination is unclear, however, it is certainly synonymous with Ehrenberg's (1843a) species of Arcella. Penard has erroneously been cited as the author of discoides.

Strain: *Centropyxis aculeata* “ecornis”

Figure 3-2.8 - 3-2.10

Arcella ecornis EHRENBURG, 1843b, p. 410, pl. 1, part IV, fig. 9; pl. 3, part I, fig. 46.

Centropyxis ecornis (Ehrenberg). LEIDY, 1879, p. 180, pl. 30, figs. 20-34.

Centropyxis aculeata var. ecornis (Ehrenberg). PENARD, 1890, p. 150, pl. 5, figs. 45-48.

Diagnosis. -- A strain of Centropyxis aculeata with a spineless hemispherical test and a sub-terminal aperture.

Description. -- Test yellow or brown, circular to ovoid, aboral region spherical tapering from the mid-body position to the apertural lip; surface rough in aboral region grading to smooth in the apertural region; xenosomes composed of irregular mineral grains; aperture invaginated, oval or circular, sub-terminal with a thick apertural rim; length of test 70 - 100 μm , width 60 - 90 μm , height 50 - 75 μm and diameter of aperture 30 - 45 μm .

Remarks. -- The “ecornis” strain of Centropyxis aculeata is usually heavily encrusted with quartz grains. Variation occurs mainly in the coarseness of the xenosomes and thus the smoothness of the test outline. The specimens of Centropyxis ecornis from Lake Winnipeg are half the size of those described by Ogden and Hedley (1980) but are consistent with specimens of Cash and Hopkinson (1905) who described this strain as a smaller, spineless variety of Centropyxis aculeata.

***Centropyxis constricta* (Ehrenberg, 1843b)**

Figure 3-2.11 - 3-2.12

Arcella constricta EHRENBURG, 1843b, p. 410, pl. 4, fig. 35; pl. 5, fig. 1.

Diffugia constricta (Ehrenberg). LEIDY, 1879, p. 120, pl. 18, figs. 8-55.

Diffugia constricta var. elongata PENARD, 1890, p. 149, pl. 5, figs. 17-20.

Centropyxis constricta (Ehrenberg). DEFLANDRE, 1929, p. 340, text-figs. 60-67.

Description. -- Test colourless, yellow or brown; ovoid or elliptical in dorsal view, anterior angle between dorsal side and apertural face 45 - 60°; posterior obtusely rounded, often encrusted with coarser-grained xenosomes; ventral side relatively small; large,

circular or oval antero-marginal, invaginated aperture; test length 100 -120 μm , width 70 - 90 μm , height approximately 75 μm and aperture diameter 50 - 60 μm .

Remarks. -- Centropyxis constricta is rare in Lake Winnipeg sediments but still exhibits a wide variation in coarseness of the posterior xenosomes, overall test shape and anterior angle. This is consistent with other studies, in which Centropyxis constricta was described as a highly variable species (Medioli and Scott, 1983; Cash and Hopkinson, 1905). Spinous forms, common in other lakes, are unexplainably absent from the Lake Winnipeg material. The morphology of this species grades into Centropyxis aculeata “ecornis” but can be differentiated from it by the ovoid test and antero-marginal aperture.

Family DIFFLUGIIDAE Stein, 1859

Genus *Diffflugia* Leclerc in Lamarck, 1816

Type species. -- Diffflugia protaeiformis Lamarck, 1816, p. 95.

Description. -- Test globular, elongate, pyriform, or acuminate, typically circular in section, may possess one or more spines; wall with pseudochitinous base and variable amounts of agglutinated material; aperture rounded, may be somewhat produced. (Fresh water lakes and ponds.)

Diffflugia protaeiformis Lamarck, 1816

Strain: *Diffflugia protaeiformis* “protaeiformis”

Figure 3-2.13 - 3-2.15

Diffflugia protaeiformis LAMARCK, 1816, p. 95.

Diffflugia acuminata EHRENBURG, 1838, p. 131, pl. 9, fig. 3; LEIDY, 1979 (part), pl. 13, figs. 7,9,13,16,18-25; CASH and HOPKINSON, 1909, p. 19, pl. 18, fig. 12-13.

Diffflugia acaulis PERTY, 1849, p. 167.

Diffflugia proteiformis Lamarck morph “proteiformis” [sic] ASIOLI, MEDIOLI and PATTERSON, 1996, p. 250, pl. 2, fig. 1.

Diagnosis. -- Representatives of Diffflugia protaeiformis with elongate cylindrical tests; width:length ratio 0.35.

Description. -- Test variable, cylindroconical or slightly pyriform, fundus acuminate or prolonged into a blunt process by smooth curves, sides taper slightly towards aperture, neck usually long; composed of mineral grains of very fine to fine silt size; aperture large, terminal, circular; length 190 - 250 μm , diameter 65 - 85 μm , aperture diameter 30 - 60 μm .

Remarks. -- Figure 3-2.13 - 3-2.15 illustrate the three end-member forms of this extremely variable strain of Diffflugia protaeiformis. The wide range of intermediate morphologies made it difficult and probably unwise to subdivide the group further. Variability occurs in the size of the fundal process, test shape, and coarseness of the xenosomes. Most specimens are intermediate between Figure 3-2.13 and 3-2.14, with coarse-grained individuals being rather rare. Fine-grained specimens with prolonged fundal spines are also rare, however, this is likely due to the more delicate spines being broken.

Strain: *Diffflugia protaeiformis* “elegans”

Figure 3-2.16 - 3-2.17

Diffflugia protaeiformis LAMARCK, 1816, p. 95.

Diffflugia acuminata Ehrenberg. LEIDY, 1979 (part), pl. 13, figs. 5,10-11,14,17.

Diffflugia elegans PENARD, 1890 (junior homonym of Diffflugia elegans Leidy, 1874a), p. 140, pl. 4, fig. 4-11; PENARD, 1902, p. 236, text-figs. 1-13.

Diffflugia acuminata var. elegans Penard. WEST, 1901, p. 219, pl. 28, figs. 11-12.

Diffflugia bacilliarum var. elegans Penard. CASH and HOPKINSON, 1909, p. 28, text-fig. 48, pl. 20, figs. 2-5.

Diffflugia proteiformis [sic] Lamarck morph “rapa” ASIOLI, MEDIOLI and PATTERSON, 1996, p. 250, pl. 2, fig. 3.

Diagnosis. -- Specimens of Diffflugia protaeiformis characterized by ovoid tests with slight constrictions posterior to the aperture and a fundal tubular spine.

Description. -- Test colourless to brown; ovoid, fundus acuminate and terminated by a tubular spine, sides curved and slightly inflated, frequently asymmetrical, constricted to a greater or lesser degree posterior to the aperture; circular in cross section; composed of silt-grains; aperture terminal, circular, surrounded by irregularly arranged particles; length 90 - 100 μm , diameter 40-50 μm , aperture diameter 30 - 35 μm .

Remarks. -- This strain of Diffflugia protaeiformis is described as having rod-like diatoms surrounding the aperture (Cash and Hopkinson, 1909). Diatoms are absent from Lake Winnipeg specimens; instead, the aperture is surrounded by irregularly arranged mineral grains. Penard (1902) illustrated living specimens as possessing a thick mass of diatom frustules and mineral particles covering the aperture; this apertural accumulation however, is apparently not preserved in the fossil state.

Strain: *Diffflugia protaeiformis* "inflata"

Figure 3-3.1 - 3-3.4

Diffflugia protaeiformis LAMARCK, 1816, p. 95.

Diffflugia acuminata Ehrenberg. LEIDY, 1879 (part), pl. 13, figs. 1-2,8.

Diffflugia acuminata var. inflata PENARD, 1899 (junior homonym of Diffflugia bacillifera var.

inflata Penard, 1890), p. 29, pl. 3, fig. 1; PENARD, 1902, p. 234, text-fig. 10; CASH and HOPKINSON, 1909, p. 23, pl. 18, fig. 14.

Diffflugia distenda OGDEN, 1983, p. 30, fig. 21.

Diagnosis. -- A strain of Diffflugia protaeiformis characterized by smooth-surfaced, ovoid or pyriform tests with apertures rimmed by small grains.

Description. -- Test transparent; ovoid or pyriform, symmetrical, cross section circular, fundus acutely curved and furnished with a tubular spine, sides curved and extremely inflated, narrowing towards the aperture; composed of a mosaic of small to medium quartz

grains, surface smooth; aperture terminal, circular, surrounded by an even rim of small grains; length 90 - 130 μm , diameter 60 - 90 μm , aperture diameter 25 - 40 μm .

Remarks. -- The variation exhibited by this strain of Diffugia protaeiformis is restricted to the overall outline of the test, which ranges from rounded to elongate. The specimens observed in Lake Winnipeg are considerably smaller than those described by others (Cash and Hopkinson, 1909; Ogden, 1983) but the proportions are comparable.

Diffugia protaeiformis “inflata” resembles Diffugia oblonga “lanceolata” in wall structure but can be distinguished from it by the characteristic tubular spine. The more elongate morphologies of Diffugia protaeiformis “inflata” grade into the simplest forms of Diffugia fragosa “fragosa”, however, the latter taxon lacks the typical circular cross section.

Diffugia ampullula Playfair, 1918

Figure 3-3.5 - 3-3.8

Diffugia ampullula PLAYFAIR, 1918, p. 650, pl. 37, figs. 10-11.

Description. -- Test ovoid with circular cross section, fundus hemispherical; composed mainly of small to medium xenosomes, arranged to give a clean outline and relatively smooth surface; aperture is circular, surrounded by a slightly everted collar of small particles, the edge of the collar is often irregular; length 70 - 100 μm , diameter 45 - 70 μm , aperture diameter 20 - 30 μm .

Remarks. -- The specimens observed from Lake Winnipeg differ slightly from the original description (Playfair, 1918) in possessing a fundus which is rounded rather than apiculate. However, the minute, pointed process was reported as sometimes being absent. Ogden and Hedley (1980) also reported non-apiculate specimens in their material from Britain. Variation in this species appear in the coarseness of the xenosomes and the smoothness of the surface.

Diffflugia fragosa Hempel, 1898

Strain: *Diffflugia fragosa* “fragosa”

Figure 3-3.9 - 3-3.12

Diffflugia fragosa HEMPEL, 1898, p. 320, text-figs. 1-2.

Pentagonia maroccana GAUTHIER-LIÈVRE and THOMAS, 1958, p. 349, text-fig. 56.

Maghrebia spatulata GAUTHIER-LIÈVRE and THOMAS, 1958, p. 351, pl. 13.

Diagnosis. -- Specimens of Diffflugia with irregular outlines created by large, hollow, spinous protruberances.

Description. -- Test composed of agglutinated silt grains; shape irregular, generally drop-shaped in side view with one to eight large protruberances running from the middle of the test towards the fundus, each protuberance ends in a spine; cross section triangular to octagonal or totally irregular, depending on the number and shape of the protruberances; aperture terminal, circular, surrounded by a slightly raised collar of small grains; test length 120 - 210 μm , diameter 65 - 90 μm , aperture diameter 30 - 40 μm .

Remarks. -- The simplest morphologies of Diffflugia fragosa “fragosa” grade into Diffflugia protaeiformis “inflata”. Both taxa have similar wall structure and apertural characteristics but Diffflugia fragosa “fragosa” lacks the axial symmetry of the latter.

Strain: *Diffflugia ?fragosa* “strain a”

Figure 3-3.13 - 3-3.14

Diagnosis. -- Representatives of Diffflugia with 2 or more spinous lobes extending from the lateral margin of a slightly compressed test.

Description. -- Test composed of agglutinated silt grains; shape ovoid, slightly compressed, two to nine blunt spines extend from the lateral margin, spines are irregular in size, shape and distribution; cross section elliptical with acute lateral margins or totally irregular, depending on the number, shape and distribution of the spines; aperture terminal,

circular, surrounded by a slightly raised collar of small grains; test length 90 - 110 μm , width 85 - 100 μm , aperture diameter 25 - 30 μm .

Remarks. -- This strain of thecamoebians was tentatively placed in Diffflugia fragosa due to its wall structure and apertural characteristics. It was separated as a strain, however, because the test shape is not as irregular as Diffflugia fragosa "fragosa". Bluntly spinous protruberances extend only from the lateral margin of the slightly compressed test.

This strain is unique to Lake Winnipeg. It occurs in trace abundances throughout The Narrows and South Basin (Figure 3-1).

Diffflugia globulus (Ehrenberg, 1848)

Figure 3-3.15 - 3-3.16

Arcella ?globulus EHRENBURG, 1848, p. 379. EHRENBURG, 1856, p. 333, fig. 4.

Diffflugia proteiformis [sic] (Ehrenberg) subspecies globularis (Dujardin). WALLICH, 1864, p. 241, pl. 15, fig. 4h; pl. 16. figs. 1,2,2a,17, 21.

Diffflugia globulosa Dujardin. LEIDY, 1879, p. 96, pl. 15, figs. 25-31; pl. 16, figs. 1-23; PENARD, 1902, p. 256, text-figs. 5-6; OGDEN and HEDLEY, 1980, p. 134, pl. 56.

Diffflugia globulus (Ehrenberg). CASH and HOPKINSON, 1909, p. 33, text-figs. 52-54, pl. 21, figs. 5-9.

Description. -- Test globular, not compressed, no spines; composed of chitinous membrane, with agglutinated xenosomes of various sizes; surface usually somewhat rough depending on the nature of the foreign material; aperture circular, not invaginated, often large proportionately to size of test; diameter 80 - 120 μm , aperture diameter 35 - 45 μm .

Remarks. -- This is one of the most abundant species in the South Basin of Lake Winnipeg (Figure 3-1). Three globular forms, Diffflugia globulus, Cyclopyxis arcelloides, and Phryganella acropodia have been grouped under Diffflugia globulus by Medioli and Scott (1983). These three genera are distinguished mainly by the nature of their pseudopods which makes separation in fossil material difficult (Cash and Hopkinson,

1909). However, in Lake Winnipeg three distinct test morphologies are recognized, resulting in three taxa. Since the generic characteristics are not preserved, grouping all three taxa within one genus or as strains of Diffugia globulus was regarded as premature. Diffugia globulus can be distinguished from Cyclopyxis arcelloides by its non-invaginated aperture and from Phryganella acropodia by its spherical shape.

***Diffugia manicata* Penard, 1902**

Figures 3-4.1 - 3-4.2; 3-5.1 - 3-5.4

Diffugia manicata PENARD, 1902, p. 226, text figs. 1-5.

Description. -- Test yellow or brown, small, pyriform, tapering gradually from rounded fundus towards aperture, not compressed; composed of small to medium xenosomes with occasional coarse grains; surface rough, short collar composed of small particles, often large mineral grains surround the test posterior to the collar; aperture small, circular, terminal; test length 50 - 90 μm , diameter 40 - 60 μm , aperture diameter 20 -30 μm .

Remarks. -- This species was thought to be uncommon by Wailes (1919) but it is the single most abundant species in Lake Winnipeg. Ogden (1983) suggested that it may have been overlooked because of its small size. Diffugia manicata varies in the coarseness of the xenosomes and the overall shape of the test, but the collar of small particles is always distinct.

***Diffugia oblonga* Ehrenberg, 1832**

Strain: *Diffugia oblonga* "oblonga"

Figure 3-4.3 - 3-4.7

Diffugia oblonga EHRENBURG, 1832, p. 90.

Diffugia pyriformis PERTY, 1849a, p. 168; Perty 1852, p. 187, pl. 9, fig. 9.

Diagnosis. -- A strain of Diffugia oblonga with a flask-shaped test composed of medium to coarse xenosomes; width:length ratio approximately 0.5.

Description. -- Test variable in size and shape; pyriform or flask-shaped, cross section circular, fundus rounded, sides taper gradually towards the oral end, or narrow suddenly to form a short cylindrical neck; composed of very fine to medium silt grains, surface texture moderately to very rough depending on the nature of the agglutinated particles; aperture terminal, circular; test length 150 - 200 μm , diameter 70 - 100 μm , aperture diameter 30 - 50 μm .

Remarks. -- This is the most abundant of the four strains of Diffugia oblonga. Variation occurs in the shape of the test and the coarseness of the mineral grains.

Strain: *Diffugia oblonga* "lacustris"

Figure 3-4.8 - 3-4.12

Diffugia pyriformis var. lacustris PENARD, 1899, p. 24, pl. 2, fig. 11.

Diffugia oblonga var. lacustris Penard. CASH and HOPKINSON, 1909, p. 12, text-fig. 40, pl. 19, figs. 1-2.

Diffugia lacustris Penard. OGDEN, 1983, p. 9, fig. 5.

Diagnosis. -- Representatives of Diffugia oblonga with cylindrical tests of medium to coarse xenosomes; width:length ratio approximately 0.4.

Description. -- Test transparent or hyaline, elongate, slightly pyriform, or cylindrical; composed of chitinous material encrusted with xenosomes, smallest grains around the aperture often grading to coarsest grains at the fundus; surface usually moderately rough due to agglutinated particles; aperture terminal, circular, surrounded by small particles; test length 160 -240 μm , diameter 60 - 110 μm , aperture diameter 40 - 70 μm .

Remarks. -- Variation in this species is restricted to the shape of the test, which can be cylindrical, slightly pyriform or slightly tapering from the fundus to the aperture. The original description (Penard, 1899) alluded to a small constriction at the aperture occasionally being observable. This feature is usually only visible in the slightly pyriform morphology.

Strain: *Diffflugia oblonga* "lanceolata"

Figure 3-4.13 - 3-4.15

Diffflugia pyriformis LEIDY 1879 (part), p. 98, pl. 10, fig. 1,2,17.

Diffflugia lanceolata PENARD, 1890, p. 145, pl. 4, figs. 59-60; PENARD, 1902, p. 250, text-figs. 1-5.

Diagnosis. -- Specimens of *Diffflugia oblonga* with very smooth, ovoid tests composed of siliceous platy particles.

Description. -- Test yellow or colourless; lanceolate, subacute or rounded fundus, swelling rapidly to the greatest diameter, tapering gradually to the narrow oral pole; mosaic of siliceous angular scales and fine silt grains; surface very smooth; aperture terminal, circular, surrounded by a smooth rim of organic cement; length 90 -130 μm , diameter 55 - 80 μm , aperture diameter 20 -30 μm .

Remarks. -- This strain of *Diffflugia oblonga* exhibits very little variation except in the overall shape of the test, which ranges from a short inflated morphology to a more elongate outline. Penard (1890) described specimens which had an acuminate (acorn-like) or rounded fundus; in Lake Winnipeg only the latter forms were found.

Strain: *Diffflugia oblonga* "linearis"

Figure 3-4.16 - 3-4.20

Diffflugia oblonga var. *linearis* PENARD, 1890, p. 137, pl. 3, figs. 42-44.

Diffflugia linearis GAUTHIER-LIÈVRE and THOMAS, 1958, p. 315, figs. 38c-d.

Diagnosis. -- A strain of *Diffflugia oblonga* with an elongate pyriform test composed of medium to coarse xenosomes; width:length ratio 0.35 - 0.4.

Description. -- Test transparent, slim, elongate, fundus rounded or rarely sub-acute, expanding rapidly to greatest diameter, tapering evenly from just posterior of mid-body to form a long neck, sides of neck parallel; composed of xenosomes of variable grain size, coarsest grains at base of neck, smallest grains near aperture; aperture terminal, circular,

surrounded by small pieces of quartz; length 120 - 145 μm , diameter 45 - 60 μm , aperture diameter 20 - 30 μm

Remarks. -- Variation in this strain is seen in the shape of the test and the coarseness of the agglutinated grains. These xenosomes consist entirely of mineral grains. Diatom frustules were never observed as components of the test although Ogden (1983) described and illustrated tests containing a large proportion of diatomaceous xenosomes.

Diffflugia urceolata Carter, 1864

Strain: *Diffflugia urceolata* "urceolata"

Figure 3-5.5 - 3-5.7

Diffflugia urceolata CARTER, 1864, p. 27, pl. 1, fig. 7; LEIDY, 1879 (part), p. 106, pl. 14, figs. 1-2,5-10,14; pl. 16, fig. 33; pl. 19, fig. 27; MEDIOLI and SCOTT, 1983 (part), p. 31, pl. 3, figs. 7-10.

Diagnosis. -- Specimens of Diffflugia urceolata characterized by a spherical test with a conspicuous evaginated collar; width:length 0.7 - 0.9.

Description. -- Test spheroid to slightly ovoid, fundus obtusely and evenly rounded; composed of very fine to medium silt grains, surface smooth and regular; neck short, terminating in an evaginated, evaginated collar; aperture large, circular; test length 240 - 310 μm , diameter 200 - 260 μm , aperture diameter 100 - 130 μm .

Remarks. -- This distinctive strain is one of the largest thecamoebians found in Lake Winnipeg. Variation occurs in the shape of test (spherical to ovoid) and in the coarseness of the xenosomes. The coarser grains of some specimens obscure the recurved nature of the collar but it is easily recognizable in transmitted light where the collar appears heavy and opaque. Spinous morphologies described by other workers (e.g. Leidy, 1879; Ogden and Hedley, 1980) are absent from the Lake Winnipeg material.

Strain: *Diffflugia urceolata* "amphora"

Figure 3-5.8 - 3-5.9

Diffflugia urceolata CARTER, 1864, p. 27, pl. 1, fig. 7; LEIDY, 1979 (part), p. 106, pl. 14, figs. 3-4, 7-8; pl. 16, fig. 34; MEDIOLI and SCOTT, 1983 (part), p. 31, pl. 3, figs. 13-14, 18-19.

Diffflugia amphora LEIDY 1874b (junior homonym of *Diffflugia amphora* Ehrenberg, 1872), p. 79.

Diagnosis. -- Representatives of *Diffflugia urceolata* with elongate, amphora-like tests with a recurved collar; width:length ratio 0.5 - 0.6.

Description. -- Test ovoid or cylindrical, fundus rounded to subacute, plain; composed of small to medium xenosomes, surface relatively smooth and regular; neck short, terminating in an evaginated, recurved collar; aperture large, circular; test length 275 - 365 μm , diameter 170 - 200 μm , aperture diameter 90 - 130 μm .

Remarks. -- The large size and distinctive nature of this strain of *Diffflugia urceolata* make it easily distinguishable. Sometimes, however, the collar can be so strongly recurved that it virtually hides the neck.

Strain: *Diffflugia urceolata* "lebes"

Figure 3-5.10 - 3-5.11

Diffflugia urceolata CARTER, 1864, p. 27, pl. 1, fig. 7; MEDIOLI and SCOTT, 1983 (part), p. 31, pl. 3, figs. 1-6

Diffflugia urceolata var. *lebes* PENARD, 1893, p. 177, pl. 3, fig. 17.

Diffflugia lebes Penard. PENARD, 1899, p. 30, pl. 3, figs. 7,8,12; PENARD, 1902, p. 270, text-fig. 1.

Diagnosis. -- Small, spheroid to ovoid *Diffflugia urceolata* with straight, non-recurved collar.

Description. -- Test spheroid to ovoid, fundus obtusely rounded, plain; composed of small to medium grains, surface moderately smooth and regular; short evaginated collar, not recurved; aperture large, circular; test length 110 - 140 μm , diameter 90 - 100 μm , aperture diameter 40 - 50 μm .

Remarks. -- This is the smallest of the *Diffflugia urceolata* strains. Variation is largely restricted to the shape of the test and the prominence of the collar. Smaller individuals grade into *Diffflugia globulus* but can be distinguished from it by the presence of the evaginated collar. More elongate morphologies grade into *Diffflugia ampullula*, however they can be distinguished from the latter by a more pronounced collar and larger size. *Diffflugia ampullula* also tends to have a more elongate test with a smoother surface.

***Diffflugia urens* Patterson, MacKinnon, Scott and Medioli, 1985**

Figure 3-6.1 - 3-6.2

Diffflugia urens PATTERSON, MACKINNON, SCOTT and MEDIOLI, 1985, p. 135, pl. 3, figs. 5-14.

Description. -- Test brown; spherical, no spines or protruberances, composed of fine-grained mineral particles, surface moderately rough; neck short, terminated by an outward expanded flanged collar of variable width; aperture, small, circular; test diameter 70 - 80 μm , aperture diameter 10 μm .

Remarks. -- This tiny species is rare in Lake Winnipeg. It differs slightly from the original description (Patterson et al., 1985) in that it is smaller in size and composed of finer-grained material. The apertural diaphragm described by Patterson et al. (1985) was never observed in the Lake Winnipeg material, but this may be simply because the specimens were too small to discern such a detail. This species is distinguished from *Cucurbitella tricuspis* by the presence of a flanged or recurved collar and small aperture.

Diffflugia viscidula Penard, 1902

Figure 3-6.3 - 3-6.4, 3-6.7 - 3-6.8

Diffflugia viscidula PENARD, 1902, p. 259, text-figs. 1-4.

Description. -- Test opaque, pyriform or elongate ovoid, fundus rounded or rarely subacute, sides slightly convex; composed of angular mineral grains of different sizes; aperture terminal, circular, usually surrounded by small particles which give it a characteristic well-defined outline; test length 180-230 μm , diameter 95 - 140 μm , aperture diameter 50 - 75 μm .

Remarks. -- This species exhibits very little variation within the Lake Winnipeg material. It is found in low abundance in almost every sample.

Genus *Lagenodifflugia* Mediolli and Scott, 1983

Type species. -- Diffflugia vas Leidy, 1874a, p. 155.

Description. -- Test flask shaped, not compressed laterally, formed of two distinct chambers, chamber separation marked externally by a well-developed constriction, at base of neck an internal diaphragm with one perforation corresponds to the external constriction; aperture simple on top of the collar chamber. (Fresh water.)

Lagenodifflugia vas (Leidy, 1874a)

Figure 3-6.5 - 3-6.6, 3-6.9 - 3-6.10

Diffflugia vas LEIDY, 1874a, p. 155.

Pontigulasia vas (Leidy) SCHOUTEDEN, 1906, p. 338; CASH and HOPKINSON, 1909, p. 59, text-figs. 70-71, pl. 13, fig. 1.

Description. -- Main part of test ovoid, fundus rounded, sides slightly convex, cone-shaped neck extends from ovoid body, neck usually slightly longer than wide, base of the neck marked by a constriction corresponding to an internal diaphragm, cross section

circular; composed of fine silt xenosomes; aperture, terminal, circular; test length 110 - 170 μm , diameter 60 - 85 μm , aperture diameter 25 - 35 μm .

Remarks. -- The constriction at the base of the neck is not always clearly defined; some specimens have an almost continuous, pyriform outline, while the constriction in other individuals is hidden by xenosomes. In both cases, however, the internal diaphragm is visible in transmitted light as a dark line across the test. This species is relatively rare in Lake Winnipeg sediments but even a few examples exhibit a wide range of test morphology. Variation occurs in grain size of the xenosomes and in the overall shape.

Genus *Pontigulasia* Rhumbler, 1895

Type species. -- *Pontigulasia compressa* Rhumbler, 1895, p. 105.

Description. -- Test flask shaped, laterally slightly compressed, formed of two indistinct chambers; chamber separation marked externally by a faint constriction at base of neck, internal diaphragm with two perforations (occasionally one) corresponds to the external constriction; aperture elongated, simple, terminal. (Fresh water.)

Pontigulasia compressa (Carter, 1864)

Figure 3-6.11 - 3-6.12

Diffugia compressa CARTER, 1864, p. 22, pl. 1, figs. 5-6.

Diffugia elisa PENARD, 1893, p. 177. pl. 3, fig. 7.

Pontigulasia compressa RHUMBLER, 1895, p. 105, pl. 4, figs. 13a-b.

Pontigulasia incisa RHUMBLER, 1895, p. 105, pl. 4, figs. 5, 22a; Penard, 1902, p. 315, text-figs. 1-6.

Pontigulasia compressa (Carter). AVERINTSEV, 1906, p. 169.

Pontigulasia rhumbleri HOPKINSON in CASH and HOPKINSON, 1909, p. 162.

Description. -- Test pyriform, laterally compressed, fundus broadly rounded, neck well defined, tapering regularly towards the narrow aperture, junction between the neck and

body marked by constriction corresponding to an internal diaphragm; test composed of fine mineral grains, surface rough due to arrangement of xenosomes, the neck is usually smoother; aperture truncated, rounded or broadly elliptical; test length 100 - 120 μm , width 80 - 95 μm , aperture diameter 30 μm .

Remarks. -- This species is uncommon in Lake Winnipeg sediments. The constriction marking the position of the internal diaphragm is often obscured by coarse xenosomes; this internal feature is usually discernible in transmitted light, however, as a curved or "v"-shaped line at the base of the neck.

Family HYALOSPHEENIIDAE Schulze, 1877

Genus *Awerintzewia* Schouteden, 1906

Type species. -- *Heleopera cyclostoma* Penard, 1902, p. 390.

Description. -- Test ovate and compressed, composed of various-sized siliceous plates cemented in a pseudochitinous base, usually some foreign material at aboral end; aperture elliptical, terminal, surrounded by distinctly thickened border. (Aquatic vegetation and sphagnum.)

Awerintzewia cyclostoma (Penard, 1902)

Figure 3-7.1 - 3-7.2

Heleopera cyclostoma PENARD, 1902, p. 390, text-figs. 1-6.

Awerintzewia cyclostoma (Penard). SCHOUTEDEN, 1906, p. 357.

Awerintzia [sic] *cyclostoma* (Penard). WAILES, 1919, p. 64, pl. 57, figs. 12-13.

Awerintzewia cyclostoma (Penard). LOEBLICH and TAPPAN, 1964, p. C29, figs. 11.1-11.12.

Description. -- Test of moderate size, broadly ovate, compressed, composed of numerous, relatively large, quartz-grains with very small plates in intervening spaces; surface of test smooth except for adherent grains at fundus; ovate in side view; elliptical

cross section; aperture small, terminal, elliptical, bordered internally by thickened test wall; length 135 - 180 μm , width about 90 μm , thickness 60 μm , aperture 20 - 40 μm .

Remarks. -- The confusion over the spelling of the generic name is the result of transliteration of a Russian name from which it is derived. Refer to Wailes (1919) for further discussion of the problem.

Awerintzewia cyclostoma closely resembles Heleopera sphagni but can be distinguished by the elliptical aperture. Due to the compressed test, apertural views are difficult to obtain, however, the crescent-like aperture of Heleopera sphagni is often visible on the side of the test as an acute notch.

Genus ***Cucurbitella*** Penard, 1902; emend. Medioli, Scott and Abbott, 1987

Type species. -- Cucurbitella mespiliiformis Penard, 1902, p. 310; subjective junior synonym of Cucurbitella tricuspis (Carter, 1856), p. 221.

Description. -- Test ovoid to spherical, symmetrical, composed of elongated idiosomes and/or xenosomes; aperture circular, usually indented by 3-9 (occasionally more) lobes, with or without a lobated collar, collar simple organic rim to a complex double structure with an internal diaphragm. Pseudopods lobose. (Fresh water.)

Cucurbitella tricuspis (Carter, 1856)

Figure 3-6.13 - 3-6.16

Diffugia tricuspis, CARTER, 1856, p. 221, pl. 7, fig. 80.

Cucurbitella tricuspis (Carter). MEDIOLI, SCOTT and ABBOTT, 1987, p. 42, pls. 1-4, text-figs. 1,4.

Description. -- Test ovate, ovoid or nearly spherical, not compressed, fundus obtusely rounded; usually composed of fine silt; aperture terminal, three (rarely four) lobes; test length 80 -140 μm , width 60 - 128 μm , aperture diameter 24 - 48 μm .

Remarks. -- Medioli et al. (1987) repositioned and re-defined the genus Cucurbitella due to the occurrence of purely autogenous tests, something not previously recorded in the family Diffugiidae; at that time they transferred Diffugia tricuspis to Cucurbitella. All specimens examined from Lake Winnipeg had tests composed entirely of xenosomes.

Cucurbitella tricuspis is relatively rare in Lake Winnipeg except in the surface sediments of the South Basin (Figure 3-1) where it is an indicator of eutrophic conditions (Burbidge and Schröder-Adams, in press).

***Cucurbitella corona* (Wallich, 1864)**

Figure 3-5.12 - 3-5.15

Diffugia proteiformis (Ehrenberg) subspecies globularis (Dujardin) var. corona WALLICH, 1864, p. 244, pl. 15, figs. 4b, ?4a, ?4c; pl. 16, figs. 19-20.

Diffugia corona Wallich. ARCHER, 1866, p. 186.

Cucurbitella corona (Wallich) HAMAN and KOHL, 1994, p. 227, pl. 3, figs. 1-8.

Description. -- Test ovoid to subcylindrical, circular in cross section; fundus furnished with a variable number of spines (1 - 4), highly variable in size and shape; test composed of a mosaic of fine, angular quartz xenosomes of various sizes, surface smooth; aperture terminal, central, roughly circular, crenulated, 6 to 20 regularly spaced indentations in a thin everted collar; test length 190-250, diameter 100 - 150µm, aperture diameter 50 - 75 µm.

Remarks. -- This is one of the few large (> 200 µm) taxa found in Lake Winnipeg. The tests differ from those observed elsewhere (e.g. Leidy, 1879; Cash and Hopkinson, 1909) in that they are distinctly elongate. Medioli and Scott (1983) described this species as having 1 to 10 (or more) delicate spines; however, tests from Lake Winnipeg rarely have more than 4 spines and these are usually quite robust.

Haman and Kohl (1994) reported the recovery of autogenous specimens thus necessitating the placement of Diffflugia corona in the genus Cucurbitella. Only xenosomic tests were observed in the material from Lake Winnipeg.

Genus *Heleopera* Leidy, 1879

Type species. -- Heleopera picta Leidy, 1879, p. 162 (= Diffflugia sphagni Leidy, 1874a).

Description. -- Test ovoid, laterally much compressed; xenogenous, siliceous plates of other thecamoebians or mineral xenosomes, few mineral xenosomes at the fundus; aperture terminal, a narrow slit in tests made of siliceous plates or widely elliptical in tests made of mineral xenosomes. (Fresh water.)

Heleopera sphagni (Leidy, 1874a)

Figure 3-7.3 - 3-7.4, 3-7.7 - 3-7.8

Diffflugia (Nebela) sphagni LEIDY, 1874a, p. 157.

Nebela sphagni (Leidy). LEIDY, 1876, p. 118, text-figs. 16-17.

Heleopera picta LEIDY, 1879, p. 162, pl. 26, figs. 1-11.

Heleopera petricola LEIDY, 1879, p. 165, pl. 26, figs. 12-20.

Heleopera sphagni (Leidy). CASH and HOPKINSON, 1909, p. 143, pl. 30, figs. 4-9.

Description. -- Test colourless, yellow, rarely brown; broadly ovoid, bi-convex, compressed especially towards oral pole, aboral end broadly rounded and rough with xenosomes; composed of chitinous membrane paved with transparent, siliceous plates and/or xenosomes; narrow slit aperture, terminal, extending to lateral edges to form an acute notch, sometimes a slight thickening of the test wall surrounding the aperture; length 100 - 130 μm ; width 60 - 80 μm , thickness 40 - 50 μm .

Remarks. -- In Lake Winnipeg this species is characterized by parallel sides which give the test a distinctly square profile at the oral pole. In other material Heleopera sphagni tapers towards the aperture resulting in a ovate outline (Medioli and Scott, 1983). This

species exhibits little variation except in the grain-size of the xenosomes and the opening width of the aperture. It is easily distinguished from Awerintzewia cyclostoma by its slit-like aperture.

Genus *Lesquereusia* Schlumberger, 1845

Type species. -- Lesquereusia jurassica Schlumberger, 1845, p. 255.

Description. -- Test asymmetrical flask shaped, ovoid or globose, compressed, neck asymmetrical giving the test a pseudocoiled appearance; autogenous and made of vermicular siliceous rods or xenogenous made of mineral xenosomes; forms intermediate between the previous two are quite common; round aperture at end of neck. (Fresh water.)

Lesquereusia spiralis (Ehrenberg, 1840)

Figure 3-7.5 - 3-7.6, 3-7.9 -3-7.10

Diffugia spiralis EHRENBURG, 1840, p. 199.

Lesquereusia (Diffugia) spiralis (Ehrenberg). BÜTSCHLI, 1880, pl. 3, fig. 9.

Lesquereusia spiralis (Ehrenberg). TARÁNEK, 1881, p. 228.

Description. -- Test globose or ovoid, slightly compressed, produced into an asymmetrical neck, constricted at base of neck to appear spiral; interior partition separating the neck from the body corresponds to the external constriction; wall composed of xenosomes; aperture circular or slightly oval, terminal; length 100 - 120 μm , width 90 - 100 μm , aperture diameter 30 μm .

Remarks. -- The constriction at the base of the neck is not always conspicuous; some specimens have deep indentation while others have only a slight depression. Variation is also observed in the grain size of the xenosomes and the shape of the main body of the test. Lesquereusia spiralis is reported to commonly be characterized by vermiform siliceous idiosomes (Ogden and Hedley, 1980). This feature of the test was never observed in the Lake Winnipeg material.

Family PLAGIOPYXIDAE Bonnet, 1959

Genus *Oopyxis* Jung, 1942

Type species. -- *Oopyxis cophostoma* Jung, 1942, p. 294.

Description. -- Test pseudochitinous with agglutinated foreign matter; colourless to brown; plano-convex discoid, small aperture, anteriorly eccentric. (Fresh water.)

Oopyxis sp.

Figure 3-7.11 - 3-7.12

Description. -- Test colourless to yellow; hemispherical, plano- or slightly concavo-convex; surface smooth, agglutinated mineral grains form interlocking mosaic; aperture small, oval, sub-terminal, not invaginated; test diameter 80 - 90 μm , approximate height 45 μm , aperture 20 - 30 μm .

Remarks. -- *Oopyxis* sp. is rare in Lake Winnipeg sediments. It closely resembles *Bullinularia indica* (Penard) but lacks its characteristic apertural overlap.

Family TRIGONOPYXIDAE Loeblich and Tappan, 1964

Genus *Trigonopyxis* Penard, 1912

Type species. -- *Diffflugia arcula* Leidy, 1879, p. 116.

Description. -- Test hemispherical, consisting of parchment-like membrane with included foreign mineral and vegetable matter; aperture triangular or tri-radial, rarely quadrangular or irregular. (Fresh water.)

Trigonopyxis arcula (Leidy, 1879)

Figure 3-7.13

Diffflugia arcula LEIDY, 1879, p. 116, pl. 15, figs. 34-37; pl. 16, figs. 30-31.

Trigonopyxis arcula (Leidy). PENARD, 1912, p. 9.

Description. -- Test light brown, hemispherical, slightly concave base, aboral surface regularly arched, agglutinated with fine mineral grains; ventral surface smooth, covered by organic cement; aperture small, triangular or irregularly trilobed, central, surrounded by small raised collar; basal diameter 90 - 120 μm , height 50 - 65 μm , diameter of aperture 25 μm .

Remarks. -- Trigonopyxis arcua is rare in Lake Winnipeg sediments. It can be difficult to distinguish from Centropyxis aculeata "discoides" or Arcella vulgaris because the depression in the apertural face can become clogged obscuring the true nature of the aperture.

Genus *Cyclopyxis* Deflandre, 1929

Type species. -- Centropyxis arcelloides Penard, 1902, p. 309.

Description. -- Test hemispherical plano-convex with radial symmetry, rarely with truncated margin; aperture circular, large, symmetrical.

Cyclopyxis arcelloides (Penard, 1902)

Figure 3-7.14 - 3-7.16

Centropyxis arcelloides PENARD, 1902, p. 309, text-figs. 1-4.

Cyclopyxis arcelloides (Penard). DEFLANDRE, 1929, p. 330.

Description. -- Test brown, hemispherical with rounded basal angle, agglutinated, composed of a chitinous membrane covered with small siliceous particles; test surface slightly rough; aperture large, central, slightly invaginated; test diameter 60-90 μm ; approximate height 40 μm , aperture diameter 35 - 45 μm .

Remarks. -- Cyclopyxis arcelloides is one of the species which are difficult to distinguish from Diffugia globulus in the fossil state. In this study it encompasses specimens which are hemispherical rather than globular. This species also has a slightly invaginated aperture but as discussed by Medioli and Scott (1983) the invagination can be difficult to discern.

Cyclopyxis arcelloides differs from Centropyxis aculeata in radial symmetry and from Trigonopyxis arcua in the large rounded symmetrical aperture.

Superfamily CRIPTODIFFLUGIACEA Jung, 1942

Family PHRYGANELLIDAE Jung, 1942

Genus *Phryganella* Penard, 1902

Type species. -- Phryganella nidulus, Penard, 1902, p. 418.

Description. -- Similar to Diffugia (test globular, circular in section, agglutinated, with circular, terminal aperture) but with anastomosing pseudopodia rather than simple lobose pseudopodia.

Phryganella acropodia (Hertwig and Lesser, 1874)

Figure 3-8.1 - 3-8.6

Diffugia acropodia HERTWIG and LESSER, 1874, p. 107, pl. 2, fig. 6.

Pseudodiffugia hemispherica PENARD, 1890, p. 169, pl. 7, figs. 108-114.

Phryganella hemispherica (Penard). PENARD, 1902, p. 421, text-figs. 1-5.

Phryganella acropodia (Hertwig and Lesser). CASH and HOPKINSON 1909, p. 74, pl. 20, figs. 13-14.

Description. -- Test yellowish or brownish, semi-transparent; hemispherical, flattened, circular outline in ventral view; covered with silt-grains; aperture, large, concentric; test diameter 60 - 90 μm , test height 20 - 35 μm , aperture diameter 45 - 55 μm .

Remarks. -- Phryganella acropodia is another species which is virtually impossible to differentiate from Diffugia globulus in the fossil state. Although the specimens from this study may represent a strain of Diffugia globulus they have, for the time being, been given the name Phryganella acropodia. This name refers to individuals which are hemispherical and flattened and have very large apertures.

Class RETICULAREA Lankester, 1885

Subclass FILOSIA Leidy, 1879

Order GROMIDA Claparède and Lachmann, 1859

Family EUGLYPHIDAE Wallich, 1864

Genus *Euglypha* Dujardin, 1840

Type species. -- *Euglypha tuberculata* Dujardin, 1841, p. 251.

Description. -- Test autogenous, composed of circular, oval or scutiform siliceous idiosomes regularly arranged; shape ovoid to acuminate, slightly compressed, cross section rounded, may possess spines; aperture terminal, rounded, denticulate. (Freshwater on vegetation.)

Euglypha alveolata Dujardin, 1841

Figure 3-8.7 - 3-8.8

Euglypha alveolata DUJARDIN, 1841, p. 252, pl. 2, figs. 9-10.

Description. -- Test transparent, colourless, ovoid, rarely slightly compressed, cross section circular or slightly oval; fundus broad, obtusely rounded, rarely subacute, sides tapering to aperture; composed of autogenous siliceous plates, plates generally oval or ovate or cordate, arranged in longitudinal rows in alternating series, overlapping; aperture truncated, circular, surrounded by 4 - 12 angular, denticulate points formed by the anterior series of plates; test length 100 - 120 μm , width 50 - 60 μm , aperture diameter 25 - 30 μm .

Remarks. -- This extremely rare species is the only observed autogenous taxon in Lake Winnipeg. It is always composed entirely of idiosomes. Large, well developed specimens of *Euglypha alveolata* possess 4 - 6 thorn-like spines (Leidy, 1879), but tests from the Lake Winnipeg material are small and lack fundal spines. This suggests that this species is not well developed in Lake Winnipeg.

ACKNOWLEDGEMENTS

We are grateful to Mike Lewis, Harvey Thorleifson and Brian Todd for giving us the opportunity to join this project. We would also like to thank the shipboard scientists and crew of the Namao for supplying the samples. Assistance on the SEM was provided by C. Huang and L. Ling. The research was funded by a research grant of the Natural Sciences and Engineering Research Council of Canada to C.J. Schröder-Adams and an Ontario Graduate Scholarship to S.M. Burbidge.

Figure 3-1: Location map showing coring sites selected for thecamoebian analysis.

Figure 3-2: SEM images of selected taxa.

1 Arcella vulgaris, apertural view, x 400.

2-5 Centropyxis aculeata “aculeata” showing variable number and arrangement of spines;

2, apertural view, aperture partially blocked by debris, x 500;

3, apertural view of a specimen with three spines, x 300;

4, apertural view of a specimen with one spine, x 440;

5, dorsal view of a specimen with three spines, x 370.

6-7 Centropyxis aculeata “discoides”

6, apertural view, x 475;

7, slightly oblique side view, x 470.

8-10 Centropyxis aculeata “ecornis” illustrating the range of xenosome size;

8, apertural view of a specimen with coarse-grained xenosomes, x 600;

9, apertural view of a specimen with medium-grained xenosomes, x 660;

10, apertural view of a specimen with coarsest xenosomes at fundus, x 660.

11-12 Centropyxis constricta;

11, apertural view of an ovoid specimen, x 560;

12, dorsal view of a rounded specimen, x 450.

13-15 Diffugia protaeiformis “protaeiformis” showing the variation in test shape and xenosome size;

13, side view of acuminate test, x 290;

14, side view of a specimen with rounded test and small fundal process, x 330;

15, side view of coarse-grained specimen with a large fundal process, x 500.

16-17 Diffugia protaeiformis “elegans”;

16, side view of test, x 620;

17, side view of a specimen with long fundal process, x 575.

Figure 10: SEM images

Figure 3-3: SEM images of selected taxa.

1-4 Diffflugia protaeiformis “inflata” showing smooth mosaic surface and the variation in test shape;

- 1, side view of typical specimen, x 460;
- 2, side view of a specimen with a blunt fundal process, x 520;
- 3, side view of a specimen with a narrow test, x 560;
- 4, oblique apertural view, x 630.

5-8 Diffflugia ampullula showing variation in grain size;

- 5, side view, x 520;
- 6, side view of a relatively fine-grained specimen, x 550;
- 7, side view of a relatively coarse-grained specimen, x 600;
- 8, oblique apertural view, x 770.

9-12 Diffflugia fragosa “fragosa” illustrating variation in test shape;

- 9, side view of a multi-ribbed specimen, x 480;
- 10, side view of a specimen with two spines, x 400;
- 11, side view of a test with one spine, x 460;
- 12, oblique apertural view, x 570.

13-14 Diffflugia ?fragosa “strain a”;

- 13, oblique apertural view, x 510;
- 14, side view, x 530.

15-16 Diffflugia globulus;

- 15, side view, x 580;
- 16, apertural view, x 480.

Figure 1. SEM images of

Favosites sp. (scale bar = 1 mm)

Figure 3-4: SEM images of selected taxa.

1-2 Diffflugia manicata illustrating range of test shape;

- 1, side view of pyriform specimen with distinct collar, x 580;
- 2, side view of ovoid specimen, x 550.

3-7 Diffflugia oblonga "oblonga" showing variation in test shape and xenosome grain size;

- 3, side view of typical specimen, x 370;
- 4, side view of flask-shaped specimen, x 360;
- 5, side view, x 320;
- 6, side view, x 700;
- 7, side view of coarse-grained specimen, x 400.

8-12 Diffflugia oblonga "lacustris" showing variation of test shape;

- 8, side view of pyriform specimen, x 530;
- 9, side view of typical specimen, x 260;
- 10, side view of cylindrical specimen, x 630;
- 11, side view of narrow cylindrical specimen, x 250;
- 12, oblique apertural view, x 375.

13-15 Diffflugia oblonga "lanceolata" illustrating the smooth mosaic surface and range of test shape;

- 13, side view of narrow specimen, x 600;
- 14, side view of inflated specimen, x 720;
- 15, oblique apertural view, x 770.

16-20 Diffflugia oblonga "linearis" showing variation in test shape and grain size;

- 16, side view of fine-grained specimen, x 550;
- 17, side view of a specimen with an acutely rounded fundus, x 560;
- 18, side view of typical specimen, x 530;
- 19, side view of a coarse-grained specimen, x 525;
- 20, oblique apertural view, x 650.

Figure 3-5: SEM images of
Ammonia sp. shells.

Figure 3-5: SEM images of selected taxa.

1-4 Diffflugia manicata showing variation in grain size;

- 1, side view of a relatively coarse-grained specimen with distinct collar, x 530;
- 2, side view of a relatively fine-grained specimen, x 530;
- 3, oblique apertural view of a coarse-grained specimen, x 650;
- 4, slightly oblique apertural view, x 560.

5-7 Diffflugia urceolata "urceolata";

- 5, side view of typical specimen, x 240;
- 6, side view, x 270;
- 7, side view of a relatively coarse-grained specimen, x 240.

8-9 Diffflugia urceolata "amphora";

- 8, side view of a cylindrical specimen, x 200;
- 9, side view of an ovoid specimen, x 250.

10-11 Diffflugia urceolata "lebes";

- 10, oblique apertural view of a spherical specimen, x 600;
- 11, side view of an elongate specimen, x 500.

12-15 Cucurbitella corona showing the smooth surface and variability in test shape;

- 12, side view of a specimen with three (broken) spines, x 100;
- 13, side view of a test with two long spines, x 280;
- 14, side view of a more spherical specimen, x 270;
- 15, apertural view showing the crenulated aperture, x 430.

Figure 3-6 SEM images of

15 different species

Figure 3-6: SEM images of selected taxa.

1-2 Diffflugia urens;

1, side view showing the spherical test, x 750;

2, apertural view, x 800.

3-4,7-8 Diffflugia viscidula showing variation in test shape and grain size;

3, side view, x 330;

4, side view, x 300;

7, side view showing rough surface, x 350;

8, apertural view, x 400.

5-6,9-10, Lagenodiffflugia vas illustrating range of grain size and test shape;

5, side view of a relatively fine-grained specimen, x 630;

6, side view of a relatively coarse-grained specimen, x 600;

9, side view of narrow test, x 575;

10, oblique apertural view, x 630.

11-12 Pontigulasia compressa;

11, side view, x 530;

12, side view of a relatively coarse-grained specimen, x 530.

13-16 Cucurbitella tricuspis;

13, side view showing spherical test, x 670;

14, apertural view of previous specimen showing lobate aperture, x 700;

15, side view, x 730;

16, apertural view of previous specimen, x 700.

Figure 3-7 SEM images of *Leptocarpus*3-2 *Leptocarpus* sp. (continued)

Figure 3-7: SEM images of selected taxa.

1-2 Awerintzewia cyclostoma;

1, side view showing coarse-grained fundus, x 450;

2, apertural view showing elliptical aperture and compressed test, x 450.

3-4, 7-8 Heleopera sphagni showing variations in grain size and aperture shape;

3, side view of a relatively coarse-grained specimen, x 530;

4, apertural view of previous specimen showing slit-like aperture and compressed test, x 890;

7, apertural view, x 900;

8, side view of a typical specimen, x 580.

5-6,9-10 Lesquereusia spiralis;

5, side view of a specimen with an indistinct constriction at base of neck, x 620;

6, apertural view, x 660;

9, side view of a specimen with a distinct constriction, x 530;

10, side view of a specimen with a slightly inflated test, x 520.

11-12 Oopyxis sp.;

11, apertural view showing elliptical, subterminal aperture, x 750;

12, dorsal view showing smooth test, x 800.

13, Trigonopyxis arcula, apertural view showing triangular aperture, x 340.

14-16 Cyclopyxis arcelloides;

14, apertural view showing large central aperture, x 830;

15, dorsal view, x 750;

16, oblique side view showing slightly invaginated aperture, x 820.

Figure 3-8: SEM images of selected taxa.

1-6 Phryganella acropodia illustrating grain size variation;

- 1, apertural view of a relatively coarse-grained specimen, x 835;
- 2, apertural view of a typical specimen, x 820;
- 3, apertural view of a relatively fine-grained specimen, x 700;
- 4, side view of typical specimen, x 840;
- 5, dorsal view of a relatively coarse-grained specimen, x 790;
- 6, dorsal view of a typical specimen, x 760.

7-8 Euglypha alveolata;

- 7, apertural view showing denticulate points around aperture, x 1000;
- 8, side view showing arrangement of autogenous plates, x 750.

CHAPTER 4.
THECAMOEBIANS IN LAKE WINNIPEG:
A TOOL FOR HOLOCENE PALEOLIMNOLOGY

ABSTRACT

Holocene sediments in Lake Winnipeg are composed of the lower Lake Agassiz sequence which is unconformably overlain by the Lake Winnipeg sequence. Nine sites, covering the North and South basins and the connecting Narrows, were selected for analysis of Holocene changes in thecamoebian faunae. Only the Lake Winnipeg sequence contains thecamoebians.

This study indicates that biologic productivity and consequently the type of organic material in the sediments is the main control on thecamoebian taxa in Lake Winnipeg. Other factors controlling the distribution of thecamoebians are water chemistry and turbidity. Inorganic sediment geochemistry and water temperature do not appear to significantly influence the thecamoebian fauna of Lake Winnipeg.

Variations in the abundance of key thecamoebian species along a north-south transect divide Lake Winnipeg into three distinct areas. The North Basin has remained relatively unchanged since the retreat of Lake Agassiz as indicated by the domination of Diffflugia manicata throughout its history. This species appears to prefer Cyanophyta and diatoms as its food sources. In The Narrows harsh conditions created by turbid waters and lack of algal food taxa result in Centropyxis aculeata replacing Diffflugia manicata as the dominant species. In the South Basin three thecamoebian assemblages are recognized. Cucurbitella tricuspis, indicative of eutrophic conditions, dominates the most recent sediments of the South Basin. The underlying sediments are characterized by Diffflugia globulus. In Lake Winnipeg this species is not a cold climate (arctic) indicator as suggested elsewhere but instead seems to prefer sediments containing green and yellow-green algal material. A Centropyxis-Arcella Assemblage occurs only at the base of the southernmost

core where it is indicative of an early phase of hyposaline conditions as developed in shallow pools during the southward transgression of Lake Winnipeg.

This study illustrates the usefulness of thecamoebians as paleolimnological indicators. Environmental changes are more significant in the restricted South Basin, resulting in distinct thecamoebian assemblages. In contrast, the North Basin provided a stable environment throughout the late Holocene reflected in only subtle faunal changes.

INTRODUCTION

Thecamoebians are an informal group of testate protozoans also referred to as agglutinated rhizopods or testate amoebae. These small benthic rhizopods (<45-300 μm) have a saclike test with a simple aperture for the extrusion of pseudopods. Tests can be secreted by the organism (autogenous tests) or built by agglutinating foreign particles (xenogenous tests) in autogenous cement (Ogden and Hedley, 1980). The nature of the xenosomes varies from sand grains to diatom frustules and their nature appears to be controlled by the composition of the substrate (Medioli et al., 1987).

Thecamoebians feed mainly upon bacteria, fungi, algae or other protozoans (Ogden and Hedley, 1980). The size of the test is probably controlled to a large degree by the volume of cytoplasm available in the parent test at the time of asexual fission which is, in turn, largely influenced by the availability of food in the period preceding reproduction (Medioli and Scott, 1988).

Encystment occurs in a large number of thecamoebian species as a means of rest, dormancy or defense (Ogden and Hedley, 1980). Cysts are capable of withstanding extreme environmental conditions such as desiccation, freezing or lack of food. Encystment capability allows thecamoebians to be readily transported and distributed, while still alive, over long distances by a variety of agents. Thecamoebians have a worldwide distribution, inhabiting a variety of freshwater environments ranging from mosses and soils to lakes and ponds. Their known stratigraphic range extends to the Carboniferous (Thibaut et al., 1987).

Because their tests resist dissolution in low pH environments, unlike calcareous freshwater organisms such as molluscs and ostracods, thecamoebians are commonly preserved making this group a useful paleolimnological tool (Medioli and Scott, 1988). Although these attributes suggest thecamoebians would be good paleolimnologic indicators, their ecologic requirements are poorly understood. Most early work on thecamoebians has been of taxonomic nature with little or no environmental interpretation

(e.g., Leidy, 1879; Penard, 1902; Cash and Hopkinson, 1909). Studies have shown that thecamoebian assemblages may vary throughout lake history. However, ecological controls have only been established for a small number of species due to the lack of information about lake chemistry. A few of the more recent studies have made correlations to parameters such as organic material or chemical pollutants in the sediment, trophic grade of the lake, climatic conditions, or rate of clastic input (e.g., Collins et al., 1990; McCarthy et al., 1985; Asioli et al., 1996). These studies have concentrated on small lakes. With the exception of Scott and Medioli (1983), very little thecamoebian research has been done on large lakes such as the Canadian Great Lakes or Lake Winnipeg.

Despite Lake Winnipeg being the eleventh largest lake in the world, covering over 24,000 km² and being vital to Manitoba's economy for hydroelectricity, fisheries and recreation, little scientific investigation has been carried out. The Freshwater Institute of Fisheries and Oceans Canada completed a limnological survey in 1969 which included the collection of bottom sediment samples and short cores. But no thecamoebian analysis was performed on these samples. The Lake Winnipeg Project was proposed in 1993 to study the geological history of the lake and its predecessor, Lake Agassiz and the nature of sedimentary deposits within the Lake Winnipeg basin. The survey, designated Namao 94-900, was carried out in August, 1994. This comprehensive study included a geophysical survey (seismic reflection and sidescan sonar), sediment sampling (piston cores, box cores and grab samples), water column analyses (water temperature, transparency and conductivity), plankton sampling and water sampling. Because of its multidisciplinary nature, the Lake Winnipeg Project has the potential to significantly add to our understanding of the ecological requirements of thecamoebians.

LOCATION

Lake Winnipeg is situated over the contact between the Precambrian granitic and gneissic rocks of the Superior Province to the east and the Paleozoic carbonates and

siliciclastics to the west (Manitoba Minerals Division, 1987). It is an integral part of the Nelson River drainage basin which extends from the Rocky Mountains to Hudson Bay. A constriction referred to as The Narrows divides the lake into two basins, the large North Basin (approximately 240 km by 100 km) and smaller South Basin (approximately 90 km by 40 km) (Fig. 4-1). These basins have relatively flat and shallow lakebeds with water depths averaging 9 m in the South Basin and 16 m in the North Basin (Canadian Hydrographic Service, 1981). In contrast The Narrows is characterized by an irregular lake bed with water depths reaching a maximum of 61m.

The water budget of Lake Winnipeg is supported by inflows from four major river systems (the Winnipeg, Saskatchewan, Red-Assiniboine and Dauphin rivers) and numerous other streams surrounding the lake (Lewis and Todd, 1996) (Fig. 4-1). Except for the Winnipeg River, these major rivers drain areas of urbanization and agricultural activity to the south and west. As a result the waters have high alkalinity, mineral and nutrient content (Kling, 1996). The Winnipeg River, which drains from the Superior Province, is characterized by low nutrient supply and alkalinity. Thus, due to the differences in water quality (alkalinity, nutrient content, etc.) between the eastern and western sources the lake water is heterogeneous. Outflow from Lake Winnipeg is through the Nelson River at the north end of the lake.

Temperature profiles measured in August reveal water temperature is constant from the surface to the sediment-water interface, thus indicating that Lake Winnipeg is unstratified. Summer water temperatures range from 17°C in the North Basin to 19.5°C in the South Basin (Todd, 1996). From the middle of November until the end of April complete ice cover develops (Ice Thickness Climatology, 1992) and bottom water temperatures are approximately 4°C (Moss, 1988). Thus the benthic environment of Lake Winnipeg experiences seasonal variations in temperature of 12-15°C.

Two sedimentary sequences separated by an erosional unconformity are recognized in the Lake Winnipeg basin: the lower Lake Agassiz sequence and the overlying Lake

Winnipeg sequence. In the North Basin, the Lake Agassiz sequence is characterized by two units of silty clay rhythmities topped by a third unit of firm banded silty clay. Some dropstones and grit are present in the lowermost rhythmite interval. This sequence differs slightly in the South Basin where it consists of stiff to hard diffusely banded silty clay and silty clay rhythmities. Some of the sediments are orange-brown or brownish grey in colour. Dropstones and silt lenses are present in the lower part of the Lake Agassiz sequence. The Lake Winnipeg sequence consists of soft, dark olive grey, silt-clay mud. The basal erosional contact is commonly marked by sand grains and occasionally shells and plant fragments. The lowermost interval of the Lake Winnipeg sequence often displays faint, discontinuous bands of lighter grey mud (Lewis and Todd, 1996).

MATERIALS AND METHODS

Phase one of the Lake Winnipeg Project proceeded aboard the Canadian Coast Guard Ship Namoo in August 1994. Of the material collected, nine gravity or piston cores were selected for qualitative and quantitative analyses of thecamoebians, five from the north basin (103, 104a, 105, 106 and 107a) and two cores from the south basin (120 and 122) (Fig. 4-1). The remaining two cores (110 and 113) were located north and south of The Narrows. Samples were analyzed at 40 cm intervals in all cores (except Core 105) beginning with the uppermost sample (5 cm) and proceeding downcore to include at least one sample from the Lake Agassiz sequence. Core 105 was sampled every 20 cm because it contains a thin Lake Winnipeg sequence.

In the laboratory, samples were weighed to determine approximate sample size. Since drying can cause disaggregation of thecamoebian tests, materials were not dried prior to weighing. Samples were soaked in water and soda ash for 30 minutes to aid breakdown of the consolidated mud. Each sample was then gently wet-sieved through a no. 325 mesh (0.044 mm) to remove the clays. The soaking and washing process was repeated if

necessary to completely remove all mud. The washed residues were then immersed in ethanol (95%) and water for storage and examination.

Analysis was performed using a combination of transmitted and reflected light under a binocular dissecting microscope. The entire processed portion was examined and all specimens were identified and tallied. In some cases the entire sample was processed for quantitative analysis while in others weighed portions of wet sediment were processed until a minimum of 500 specimens were tallied.

Approximations of the number of tintinids, which are planktic ciliated protozoans with an agglutinated bell-shaped shell, were also made during quantitative analysis of the thecamoebians. Due to the great abundance of tintinids a fraction of each sample was counted and the value was multiplied by an appropriate factor to approximate the whole sample. Since this is only an approximation of the whole sample the product was rounded off to significant figures.

TAXONOMIC APPROACH

Since thecamoebians are non-interbreeding organisms, taxonomic identification on species level is arbitrary (Medioli and Scott, 1983). The identification process is further complicated by the wide range of intra- and interspecific variability exhibited by this group. For the purposes of this study, specimens were sorted into morphologically similar groups referred to as strains. Generally, the term strain is used by microbiologists to distinguish asexually produced organisms with high variability and thus is appropriate for designating infraspecific variations in thecamoebian test morphology (Medioli, 1997). Strains are designated by quotation marks around non-italicized descriptive latinized names or letters. Whenever possible, previously published names were used to facilitate comparison between studies. Each strain is assigned to a species according to the original designation of the taxa and/or commonly accepted synonymy found in the current literature. For example, Diffflugia oblonga “oblonga”, Diffflugia oblonga “lacustris”, Diffflugia oblonga

“lanceolata” and Diffugia oblonga “linearis” are four distinct strains of the species Diffugia oblonga. Recognition of these strains is important; the abundance or dominance of a particular strain may well be in response to distinctive environmental conditions (Asioli et al., 1996). Therefore, if thecamoebians are to be used as paleolimnological tools, the identification of ecologically influenced strains within species is vital. The faunal list of strains and species from Lake Winnipeg sediments is presented in Appendix 4-1. A summary of quantitative results is presented in Table 4-1.

Examination of thecamoebian species abundance data revealed distinct interbasinal and downcore trends in four species: Diffugia manicata, Diffugia globulus, Centropyxis aculeata and Cucurbitella tricuspis. The samples were first grouped according to the dominance of one of these key species and the resulting assemblages were named for the dominant species. For example, the Diffugia manicata Assemblage is characterized by high percentages of Diffugia manicata and erratic occurrences of species such as Diffugia oblonga “oblonga” and Diffugia viscidula. Further examination of each group showed that some could be further divided based on the co-occurrence of other taxa. If the dominant species is consistently accompanied by other species or strains it receives mixed status; such is the case for the Mixed Diffugia manicata Assemblage. The Centropyxis-Arcella Assemblage is characterized by two strains of Centropyxis aculeata and one species of Arcella, therefore generic names are used to designate this assemblage. This process resulted in the establishment of six thecamoebian assemblages. Mean percent abundance, associated standard deviation and range of percent abundance are given for important species of each assemblage (Table 4-2).

RESULTS

North Basin

Five cores were examined from the North Basin (Fig. 4-1). These cores are composed of clay-silt mud and silty fine sand of the Lake Winnipeg sequence and silty-clay

rhythmites of the Lake Agassiz sequence. In the North Basin, thicknesses of Lake Winnipeg sequence sediments differ significantly, increasing from 65 cm (Core 105) to 685 cm (Core 103). Core lithologies are presented in Figures 4-2, 4-3 and 4-4.

Lake Agassiz sediments in the North Basin are devoid of thecamoebians and tintinids but contain ostracodes and a few diatoms (Kling, 1996; Rodrigues, 1996). Lake Winnipeg sediments, in contrast contain a rich assemblage of thecamoebians and tintinids as well as other microbiota such as diatoms and ostracodes. The appearance of thecamoebians directly above the unconformity suggests that the thecamoebian population was established early in the Lake Winnipeg phase. Abundances of thecamoebians and tintinids increase upcore while ostracodes are absent from the upper Lake Winnipeg sediments. The number of specimens per gram of wet sediment varies significantly (Figs. 4-2, 4-3 and 4-4). Maximum values of approximately 700 specimens per gram of sediment are found in three of the four cores from the North Basin for which this information is available. All four cores reveal a similar profile of thecamoebian abundance regardless of the absolute values.

In the North Basin, two thecamoebian assemblages are recognized in the Lake Winnipeg sequence, the Diffflugia manicata and Mixed Diffflugia manicata assemblages (Table 4-2; Figs. 4-2, 4-3 and 4-4). These assemblages differ from each other by the abundance of Diffflugia manicata. In the Diffflugia manicata Assemblage, Diffflugia manicata comprises >46% of the thecamoebian fauna. Diffflugia oblonga “oblonga”, Diffflugia oblonga “linearis”, Diffflugia viscidula and/or Centropyxis aculeata “aculeata” occur at relatively low percentages.

In the Mixed Diffflugia manicata Assemblage, Diffflugia manicata occurs with lower abundances of 20 - 46% although remaining the most abundant species. The balance of the fauna is composed of small proportions of difflogiids such as Diffflugia ampullula, Diffflugia oblonga “oblonga”, Diffflugia oblonga “linearis”, Diffflugia viscidula and Diffflugia

fragosa. Diffflugia globulus and Centropyxis aculeata “aculeata” each have abundances of less than 20%.

The Narrows

While no cores were taken from within The Narrows, Core 110a and 113a were taken from north and south of The Narrows, respectively (Fig. 4-1). Both cores consist of approximately 2 m of clay-silt mud of the Lake Winnipeg sequence (Fig. 4-5). Neither core penetrated the Lake Agassiz sequence. A high resolution seismic reflection profile through Core 113a indicates that the Agassiz unconformity occurs at approximately 9.5 m and core recovery was only 2.14 m. No seismic profile is available through Core 110a, therefore the depth to the Agassiz unconformity is unknown.

In comparison to the North Basin, thecamoebian population is greatly reduced in The Narrows where abundances range from 10 - 50 specimens per gram (Core 110a). Both sites show an increase in the number of thecamoebians upcore and lack evidence of the decline observed near the top of the cores from the North Basin. Tintinids show similar trends in abundance and while they are still more abundant than thecamoebians their numbers are also reduced relative to the North Basin sediments. A maximum of 1900 specimens per gram of wet sediment was observed in The Narrows (sample 110-85) compared to 29,700 specimens per gram (sample 107-45) in the North Basin.

Two thecamoebian assemblages are recognized in the cores from north and south of The Narrows (Table 4-2; Fig. 4-5). The Mixed Diffflugia manicata Assemblage found in the North Basin occurs in the uppermost sediments of Core 110a. This assemblage is characterized by 20 - 46 % Diffflugia manicata and a mixed association of diffugiids, however at this site Centropyxis aculeata “aculeata” may comprise up to 20% of the thecamoebian fauna.

The Mixed Centropyxis aculeata Assemblage is characterized by an increased abundance of Centropyxis aculeata (20 - 45 %) and reduced numbers of Diffflugia manicata

(10 - 25%). The remainder of the assemblage consists of a mixed association of difflugiids in which Diffugia globulus comprises <25%. The basal sediments of Core 110a and all of Core 113a are characterized by the Mixed Centropyxis aculeata Assemblage.

South Basin

In the South Basin the Lake Agassiz and Lake Winnipeg sequences are recognized in Cores 120 and 122a (Figs. 4-6 and 4-7). The Lake Agassiz sequence is devoid of thecamoebians as was the case in the North Basin. The thecamoebian-bearing Lake Winnipeg sediments of the upper sequence range in thickness from 195 - 435 cm and consist of clay-silt mud.

Thecamoebian populations are smaller in the South Basin (90 - 600 specimens per gram of sediment; Figs. 4-6 and 4-7) than in the North Basin but exceed The Narrows population. As in the other cores the abundance of thecamoebians increases up core but in the South Basin there is a significant peak in the thecamoebian population at the top of the core. Tintinids are much less abundant in the South Basin relative to the other cores (10 - 300 specimens per gram of sediment). The general increase in abundance of tintinids up core to a peak value is similar to the trend exhibited by thecamoebians, however, in the case of tintinids, an extreme peak (710 - 4110 tintinids/gr) occurs at 45 cm rather than at the top of the core.

In the South Basin three thecamoebian assemblages can be recognized within the Lake Winnipeg sequence (Table 4-2; Figs. 4-6 and 4-7). The Centropyxis-Arcella Assemblage, found only at the base of Core 122a, is dominated by Centropyxis aculeata (> 45%) and Arcella vulgaris (8 - 36%). Only two of the three strains of Centropyxis aculeata ("aculeata" and "ecornis") are found in this assemblage. The abundance of other thecamoebians is sporadic. The second association, the Diffugia globulus Assemblage, is characterized by > 17% Diffugia globulus and low abundances of difflugiids such as Diffugia manicata (7 - 17%), Diffugia oblonga "linearis" (< 18%), Diffugia ampullula (<

12%) and Diffugia urceolata “lebes” (2 - 11%). The top portion of cores from the South Basin are occupied by the Cucurbitella tricuspidis Assemblage featuring an increase in abundance of Cucurbitella tricuspidis (> 25%) and a decline in Centropyxis aculeata “aculeata” and Diffugia globulus (< 3%).

DISCUSSION

Environmental factors which cause the absence of thecamoebians from the Lake Agassiz sediments are unclear as there is little or no thecamoebian research available from glacial lakes. In a study of modern alpine glacial snow and sediments Laminger (1972) reported a lack of thecamoebians in new snow which he attributed to lack of colonizing time. He also reported on the absence of thecamoebians from silt-sized sediments proximal to glaciers without explaining the cause. Since Lake Agassiz existed for thousands of years (Klassen, 1983), it is not likely that there was insufficient time for a population to develop. Instead, it appears that some characteristics of glacial water or lake substrate, such as dissolved ion content or turbidity, are inhospitable to thecamoebians. Cold water temperatures are not likely to prevent thecamoebian development because they commonly inhabit arctic lakes (Collins et al., 1990; Beyens et al., 1991; Kliza, 1994).

It is hypothesized that the upcore increase in thecamoebian abundance is the result of natural establishment and stabilization of the population after the retreat of Lake Agassiz. Low faunal abundances downcore are not likely the result of poor preservation, since damaged or fragmented tests were not found to increase downcore.

Diffugia manicata is the most abundant species in Lake Winnipeg. This species was described as being uncommon (Wailes, 1919), however, Ogden (1983) suggested that it is a ubiquitous species which has been overlooked. The small size of Diffugia manicata may account for it rarely being reported. In many previous thecamoebian studies, samples have been wet-sieved through a 63 µm mesh (the standard in foraminiferal studies). Most of the Diffugia manicata specimens as well as other thecamoebian species observed in this

study would have passed through a 63 μm sieve and been lost. This emphasizes a problem in comparing earlier work with the results of this study in which a 45 μm mesh was used.

Variations in the abundance of key thecamoebian species along a north-south transect divide Lake Winnipeg into three distinct areas (Fig. 4-8). Similar trends are observed in recent sediments (grab samples) from Lake Winnipeg (Torigai, 1996).

Cucurbitella tricuspis is only abundant in the upper samples of the South Basin (Fig. 4-8). This species lives as a parasite on Spyrogyra and other chlorophycean algae and as such is believed to be an indicator of eutrophic conditions (Medioli et al., 1987). In Lake Winnipeg the development of the Cucurbitella tricuspis Assemblage is accompanied by a marked increase in the thecamoebian population. Torigai (1996) also found this to be the case in her study of the recent distribution of thecamoebians in Lake Winnipeg. Similar results were reported for a Virginia lake where high total numbers of thecamoebians and high abundances of Cucurbitella tricuspis are correlated with eutrophication (Collins et al., 1990). The remainder of the fauna from the Virginia study is similar to that of the Cucurbitella tricuspis Assemblage in Lake Winnipeg. Changes in diatom and phytoplankton faunas also imply recent eutrophication of the South Basin (Kling, 1996).

The most common cause of modern eutrophication is high nutrient input, especially fertilizer runoff and sewage discharge related to human activities. However, paleomagnetic secular variation data indicate that the onset of eutrophic conditions, as indicated by the Cucurbitella tricuspis Assemblage in Core 122a (45 cm), began approximately 450 years B.P. (King and Gibson, written comm.). Permanent settlement of the Lake Winnipeg area occurred after 1870 A.D. (McLeod, 1995), therefore anthropogenic influence is limited to the uppermost sample. Evidence in the form of increased bluegreen akinetes and particulate sediment phosphorus indicates enhanced phytoplankton production began prior to the influence of human activities (Kling, 1996). This suggests a general trend towards natural eutrophication of the lake probably as a result of fundamental changes in the catchment. Pickerel Lake in North Dakota became naturally more fertile as climatic conditions changed

to favour prairie rather than woodland in the surrounding catchment (Moss, 1988). A similar climatic shift may have initiated the increased productivity which led to eutrophication of the South Basin.

Underlying the Cucurbitella tricuspidis Assemblage are samples dominated by Diffugia globulus. This species has been interpreted as an indicator of cold climate (Asioli et al., 1996; Collins et al., 1990; Schönborn, 1984) which is not confirmed by Lake Winnipeg results. During the summer, Lake Winnipeg is unstratified and lakebed temperatures may reach 20° C (Todd, 1996) implying that this species is not restricted to cold water temperatures and is able to withstand wide yearly fluctuations.

The Centropyxis-Arcella Assemblage occurs only at the base of Core 122a (Fig. 4-8). Centropyxids are often the earliest thecamoebian species to colonize an environment. Collins et al. (1990) suggest they are opportunistic species which tolerate harsh environmental conditions. Centropyxis aculeata has been interpreted as indicative of oligotrophic conditions (McCarthy et al., 1995; Schönborn, 1984). Kerr (1984) cultured this species in bacteria-rich pondwater devoid of algae, thus it appears to be well suited to nutrient-poor environments. The organic carbon content of Core 122a is the lowest (5 - 6.2 %) in sediments characterized by the Centropyxis-Arcella Assemblage which may indicate that productivity was low and the south basin was oligotrophic.

Centropyxis aculeata has also been described as a characteristic species of marginally brackish environments (Patterson et al., 1985; Scott and Medioli, 1980). Arcella is also known to inhabit slightly saline waters (Loeblich and Tappan, 1964; Medioli and Scott, 1988). Thus the dominance of these two species (65-95 % of the fauna) at the base of Core 122a implies that these samples may represent an early phase of slightly brackish conditions in Lake Winnipeg. In addition, Arcella vulgaris has been reported from boggy localities and long-standing pools (Collins et al., 1990; Leidy, 1879). This indicates that the Centropyxis-Arcella Assemblage is characteristic of an early phase in which a slightly brackish, shallow pool developed in place of the South Basin. This

interpretation is corroborated by the plant macrofossil assemblage from the base of the Lake Winnipeg sequence in Core 122a. Vance (1996) found a rich and varied assemblage which included plants similar to modern shallow water/shoreline deposits in fresh to hyposaline lakes on the Canadian prairies.

The lack of Centropyxis-Arcella Assemblage at the base of Core 120 indicates that the two areas of the South Basin experienced different early histories. Core 120 is located at the mouth of Traverse Bay which is the inlet of the Winnipeg River (Fig. 4-1). It is unlikely that a restricted pond would develop in such a location.

Centropyxis aculeata is also found in abundance in the cores from north and south of The Narrows (Fig. 4-8), however, associated with diffugiids such as Diffugia globulus. In these localities the occurrence of Centropyxis aculeata is probably due to the lack of food sources (especially algae) preferred by other thecamoebian species. The waters of The Narrows are more turbid (inferred from reduced Secchi depths relative to the North and South basins). As a result phytoplankton surveys from 1969, 1992 and 1994 indicate that productivity is reduced in The Narrows compared to the North and South basins (Kling, 1996). Reduction in phytoplankton might mean that there is insufficient food available at the sediment-water interface for mesotrophic-adapted thecamoebians. Thus, Centropyxis aculeata, a species which probably feeds on bacteria (McCarthy et al., 1995), dominates the fauna.

Towards the north the abundance of Centropyxis aculeata and Diffugia globulus decline and Diffugia manicata becomes the dominate taxon. Diffugia manicata is the most abundant species throughout the North Basin. Thus it seems that the North Basin has experienced a history of fairly constant ecological conditions without an early hyposaline phase or late eutrophication as observed in the South Basin.

Often associated with Diffugia manicata are Diffugia oblonga “oblonga”, Diffugia oblonga “linearis” and Diffugia viscidula. Diffugia oblonga is a ubiquitous species which, in other locations, often replaces Diffugia globulus or Centropyxis aculeata as the

most dominant species; in Lake Winnipeg this taxon occurs in only modest abundance. In arctic lakes Diffflugia oblonga replaced Diffflugia globulus when the organic content of sediments increased (Kliza, 1994). A study of Canadian maritime lakes showed that accelerated climatic warming during the early postglacial period resulted in a sharp increase in the organic content of lake sediments which was accompanied by an increase in Diffflugia oblonga at the expense of Centropyxis aculeata (McCarthy et al., 1995). In Lake Erie nutrient availability and consequently biologic productivity is the most significant influence on abundance of Diffflugia oblonga and thecamoebian distribution in general. In contrast, this species appears to be unaffected by variations in the bottom water oxygen concentration (Scott and Medioli, 1983). Thus it appears that Diffflugia oblonga will proliferate in any sediments which are sufficiently organic. Diffflugia oblonga tends to be most abundant in gyttja (McCarthy et al., 1995; Patterson et al., 1985). The lack of gyttja development in Lake Winnipeg probably explains the modest abundance of Diffflugia oblonga relative to Diffflugia manicata.

Since Diffflugia manicata has often been overlooked (Ogden, 1983), very little information on the ecological preferences of this species is available. In Lake Winnipeg, both Diffflugia manicata and Diffflugia oblonga are more abundant in the North Basin, suggesting that these species may favour similar environmental conditions such as an abundance of organic material in the sediments. The organic content of the North Basin sediments, however, is not particularly high (2 - 7.7 %) compared to that of the South Basin (4.8 -9.9 %). Thus it appears that the amount of organic material in sediments is not a significant control on thecamoebian distribution in Lake Winnipeg.

Algal communities differ between the North and South basins. Summer phytoplankton compositions for 1969, 1992 and 1994 indicate that chlorophyta (green algae), chrysophyta (yellow-green algae) and cryptophyta are more abundant in the South Basin while the North Basin is characterized by diatoms and cyanophyta (bluegreen algae) (Kling, 1996). This is probably due to reduced turbidity and increased light penetration;

Secchi depths in the North Basin are 2-4 times that of The Narrows and South Basin (Todd, 1996). While thecamoebians are not photosynthesizers they appear to be strongly influenced by the productivity of photosynthesizing taxa available; these algal taxa act as food sources for thecamoebians and therefore may be responsible for distribution patterns. This could imply that Diffflugia manicata, the dominant species of the North Basin, is successfully living on cyanophyta and/or diatoms. Variation in the type of organic matter might reflect these different food sources. A comparison between thecamoebian distribution and Rock-Eval data shows no correlation between total organic carbon and thecamoebian distribution but a slight affinity between faunal changes and hydrogen indices.

Fluctuations in the general increase of fauna may be related to changes in surface productivity. Large tintinid populations may be linked to enhanced production of microalgal food taxa (Kling, 1996). Variations in algal productivity have also been inferred from $\delta^{13}\text{C}$ profiles of bulk organics (algae) and cellulose (phytoplankton) for Core 103 in the North Basin. Buhay (1996) reported two significant depletions in $\delta^{13}\text{C}$ in cellulose which correspond to significant declines in the thecamoebian abundance. Depletion in $\delta^{13}\text{C}$ of both cellulose and bulk organics at 90 cm suggests that ^{12}C enrichment may be related to contributions from terrestrial sources. Kling (1996) inferred periods of winter anoxia from the occurrence of abundant pyrite framboids/spherules. Prolonged periods of hypolimnic anoxia would enhance the preservation of terrestrial organics. Anoxic bottom waters may have reduced the population of thecamoebians adapted to fully oxygenated conditions.

While thecamoebian faunas may respond to changes in the organic composition of the sediments they do not appear to react to changes in inorganic sediment geochemistry. Comparison with both major and trace element occurrences revealed no apparent correlations. Similar results were observed in remote lakes of southern Ontario (Kliza, 1997). Only under extreme conditions, such as intense industrial pollution, is

thecamoebian distribution affected by inorganic sediment/water geochemistry (Asioli et al., 1996; Patterson et al., 1996).

CONCLUSIONS

Thecamoebians provide important information on limnological changes (e.g. trophic status). It appears from this study that biologic productivity and consequently the composition of organic material in the sediments acting as food sources is the main control on thecamoebian taxa in Lake Winnipeg. Other factors controlling the distribution of thecamoebian distribution are water chemistry and turbidity. Inorganic sediment geochemistry and water temperature do not appear to be significant considerations. Climate may indirectly affect the thecamoebian distribution by influencing the lake catchment thus controlling factors such as nutrient inflow.

Conclusions about the paleoenvironmental significance of some key thecamoebian taxa can be made on the basis of their distribution in Lake Winnipeg sediments. Cucurbitella tricuspis is indicative of recent eutrophication of the South Basin. Diffflugia globulus is not a cold climate (arctic) indicator species as others have suggested. The species Centropyxis aculeata and Arcella vulgaris which dominate the earliest South Basin sediments, tolerate hyposaline conditions. In The Narrows, where Centropyxis aculeata dominates a mixed association of difflogiids, the expansion of this species is related to harsh conditions created by decreased algal food source and increased water turbulence. Diffflugia oblonga, a species which is ubiquitous whenever the sediments are sufficiently organic, is present but never dominates the fauna as is the case in other studies. This is probably because gyttja is the optimum substrate for this species and it has not developed in Lake Winnipeg. In the North Basin, Diffflugia manicata is dominant throughout the Lake Winnipeg sequence indicating that this part of the lake has remained relatively unchanged since the retreat of Lake Agassiz. The abundance of Diffflugia manicata in the North Basin is probably related to acceptance by this taxon of cyanophyta as its food source.

This study has illustrated that thecamoebians can play an important role in deciphering the paleolimnological history of Lake Winnipeg. The paucity of multidisciplinary studies utilizing thecamoebians in other freshwater environments limits the available information on limnological requirements of each species, which should be an important objective of future research.

ACKNOWLEDGMENTS

We are grateful to Mike Lewis, Harvey Thorleifson and Brian Todd for giving us the opportunity to join this project and the shipboard scientists and crew for supplying the samples. Assistance on the SEM was provided by C. Huang and L. Ling. C. Langill is thanked for laboratory assistance. Harvey Thorleifson and Penny Henderson provided helpful discussions for which we are very grateful. We would also like to thank Dr. D. Charles for his critical review of this manuscript. The research was funded by a research grant of the Natural Sciences and Engineering Research Council of Canada to C.J. Schröder-Adams and an Ontario Graduate Scholarship to S.M. Burbidge.

Table 4-1: Summary of thecamoebian occurrence in the Lake Winnipeg sequence as percent abundance. Sample 103-645 was examined but found to be devoid of thecamoebians.

Sample	Total Count	Thecamoebians/gr. sed.	Tintinids/gr. sed.	<i>Arcella vulgaris</i>	<i>Centropyxis aculeata</i> "aculeata"	<i>Centropyxis aculeata</i> "discoidea"	<i>Centropyxis aculeata</i> "ecornis"	<i>Centropyxis constricta</i>	<i>Diffugia protaeiformis</i> "elegans"	<i>Diffugia protaeiformis</i> "inflata"	<i>Diffugia ampullula</i>	<i>Diffugia fragosa</i> "fragosa"	<i>Diffugia fragosa</i> "strain a"	<i>Diffugia globulus</i>	<i>Diffugia manticata</i>	<i>Diffugia oblonga</i> "oblonga"	<i>Diffugia oblonga</i> "lacustris"	<i>Diffugia oblonga</i> "lanceolata"	<i>Diffugia oblonga</i> "linearis"	<i>Diffugia urceolata</i> "urceolata"	<i>Diffugia urceolata</i> "amphora"	<i>Diffugia urceolata</i> "lebes"	<i>Diffugia urens</i>	<i>Diffugia viscidula</i>	<i>Lagenodiffugia vas</i>	<i>Pontigulastia compressa</i>	<i>Awerthitzewia cyclostoma</i>	<i>Cucurbitella corona</i>	<i>Cucurbitella tricuspsis</i>	<i>Heleopera sphageti</i>	<i>Lesquerensia spiralis</i>	<i>Oopyxis</i> sp.	<i>Trigonopyxis arcuata</i>	<i>Cyclopyxis arcelloides</i>	<i>Phryganella acropodia</i>	<i>Euglypha alveolata</i>			
103-005	1302	87	2600	-	-	-	-	-	0.7	2.4	-	5.1	1.9	-	0.9	53.0	8.3	1.4	1.6	5.3	3.9	1.5	2.2	-	8.3	-	-	-	-	2.8	-	-	-	-	-	-	-	0.2	0.1
103-045	1935	179	3300	-	-	-	-	-	2.7	12.5	1.4	6.8	5.5	-	-	55.7	5.3	1.6	-	6.7	0.3	-	-	-	1.2	0.2	0.1	-	-	-	0.1	-	0.1	-	-	-	-	0.1	
103-085	207	20	500	-	-	-	-	-	4.3	10.6	1.0	15.5	3.9	-	5.3	20.3	3.9	2.9	-	20.3	-	-	-	-	0.5	1.0	1.4	6.3	-	-	0.5	-	2.4	-	-	-	-	-	
103-125	322	26	2100	-	-	-	-	-	11.2	9.6	0.6	18.9	3.7	-	0.9	33.9	4.7	1.2	-	0.9	-	-	-	-	0.3	-	-	-	-	-	0.3	0.3	8.1	5.3	-	-	-	-	
103-165	531	41	600	-	-	-	-	-	2.6	2.1	0.2	19.6	6.8	-	-	58.0	1.3	1.9	-	0.6	-	-	-	-	3.4	-	-	-	-	-	0.8	1.5	-	-	-	-	-	-	
103-205	1669	109	1800	-	-	-	-	-	1.7	3.5	0.4	14.6	9.0	-	-	55.2	3.9	4.4	-	0.4	0.2	-	-	-	2.5	-	-	-	-	-	0.5	0.6	-	-	-	-	-	-	
103-245	2090	89	2500	-	-	-	-	-	1.3	5.2	0.6	11.5	12.4	-	-	48.0	10.8	1.4	-	4.9	-	-	-	-	1.2	0.0	-	-	-	-	0.5	0.2	-	-	-	-	-	-	
103-285	1237	82	1000	-	-	-	-	-	0.1	0.2	3.8	-	17.0	9.8	-	55.1	4.2	3.2	-	0.2	0.3	-	-	-	2.6	-	-	-	-	-	0.5	0.2	-	-	-	-	-	0.1	
103-325	3208	113	1100	-	-	-	-	-	2.5	3.2	1.1	14.1	2.1	-	-	59.2	5.4	4.5	-	0.9	-	-	-	-	3.8	0.8	0.1	0.2	-	-	0.3	-	-	-	-	-	-	-	-
103-365	1336	83	900	-	-	-	-	-	1.6	0.1	32.1	5.6	3.1	1.6	-	27.4	9.1	0.2	3.1	8.2	-	-	-	-	4.3	0.4	1.5	0.4	0.2	-	0.7	-	-	-	-	-	-	-	0.3
103-405	1228	41	500	-	-	-	-	-	0.7	9.4	3.7	11.2	6.6	-	-	45.7	15.6	0.6	-	0.1	-	-	-	-	1.6	-	0.2	-	-	-	0.2	-	-	-	-	-	-	-	
103-445	577	27	300	-	-	-	-	-	0.7	15.1	0.5	12.3	3.6	-	-	51.1	8.0	0.7	-	-	-	-	-	-	2.9	0.5	4.0	-	0.2	-	-	-	-	-	-	-	-	-	
103-485	879	40	-	-	-	-	-	-	0.3	0.1	7.6	0.5	2.8	0.2	0.1	-	20.4	1.4	-	62.8	-	-	-	-	1.7	-	0.9	-	1.0	-	0.1	-	-	-	-	-	-	-	
103-525	92	6	100	-	-	-	-	-	6.5	25.0	-	15.2	4.3	-	-	35.9	5.4	-	-	-	-	-	-	-	1.1	-	5.4	-	-	-	-	-	-	-	-	-	-	-	
103-565	60	5	400	-	-	-	-	-	0.0	18.3	-	1.7	1.7	-	-	68.3	-	3.3	-	-	-	-	-	-	3.3	-	-	-	-	-	-	-	-	-	-	-	-	-	
103-605	118	6	300	-	-	-	-	-	0.8	8.5	-	16.9	1.7	-	-	60.2	5.1	-	-	-	-	-	-	-	3.4	-	1.7	-	-	-	-	-	-	-	-	-	-	-	-
103-685	235	12	-	-	-	-	-	-	0.4	11.9	-	12.3	-	-	-	54.5	3.0	-	-	-	-	-	-	-	16.6	-	-	-	-	-	0.4	-	-	-	-	-	-	-	-
104-005	1484	742	13500	-	1.3	-	0.3	-	1.3	0.7	-	5.9	1.9	-	3.5	62.3	3.8	3.0	-	7.8	0.7	-	0.3	-	4.9	0.1	-	-	-	-	0.5	0.1	1.3	-	-	-	-	0.3	
104-045	382	127	2000	-	5.8	-	-	0.5	1.0	6.3	-	8.6	3.1	-	5.0	54.2	5.0	-	-	3.4	0.3	0.5	1.3	-	2.4	-	-	-	-	-	0.3	1.0	0.3	-	-	-	-	1.0	
104-085	2127	532	9200	0.0	1.3	0.1	0.2	0.0	1.1	2.4	0.1	8.5	8.4	-	4.6	41.4	19.7	1.6	0.0	3.6	0.9	1.1	0.7	-	1.7	0.0	-	-	-	-	0.4	0.5	0.0	-	-	-	-	1.3	
104-125	1060	707	3500	-	1.0	-	0.7	-	0.1	1.1	0.4	9.3	1.9	-	5.0	53.7	13.1	0.4	-	0.9	1.4	0.5	0.7	1.6	5.0	-	-	-	-	-	2.5	-	0.6	0.1	-	-	-	0.1	
104-165	489	114	6700	-	3.3	-	2.0	0.2	-	0.6	0.2	1.4	0.6	-	12.5	61.3	9.2	-	-	2.7	-	-	-	-	2.7	0.4	-	-	-	-	0.2	0.2	0.8	-	-	-	-	1.6	
104-205	563	375	19300	-	1.4	-	0.7	-	1.4	2.0	0.2	7.1	6.9	-	11.0	53.8	11.0	-	-	0.2	-	-	-	-	2.5	-	-	-	-	-	-	-	0.9	-	-	-	-	0.2	
104-245	503	91	1500	0.2	1.0	-	-	-	0.8	-	-	4.6	-	-	2.6	62.4	6.4	-	-	0.2	0.6	-	-	-	20.5	-	-	-	-	-	-	0.2	0.4	-	-	-	-	0.2	
104-285	51	3	-	-	3.9	-	-	-	-	-	-	17.6	-	-	15.7	45.1	-	-	-	-	-	-	-	-	2.0	2.0	-	-	-	-	-	0.2	0.4	-	-	-	-	-	0.2
104-325	11	1	-	-	-	-	-	-	-	-	-	-	-	-	27.3	45.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.0	3.9	-	-	-	-	-	
104-365	12	1	-	-	16.7	-	-	-	-	-	-	-	-	-	8.3	75.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18.2	-	-	-	-	9.1	
105-005	1740	-	-	-	2.1	0.5	0.5	0.1	1.0	0.9	0.2	10.2	6.6	-	0.5	63.5	0.6	0.5	0.1	4.1	0.9	0.1	0.5	-	4.5	0.4	-	-	-	-	1.0	0.1	1.1	0.1	-	-	-	-	
105-025	1312	-	-	-	2.5	0.1	1.0	-	0.1	0.9	0.1	6.0	1.4	-	4.9	65.9	0.4	0.5	-	3.4	1.0	0.1	1.0	-	4.5	1.1	-	-	-	-	2.7	0.1	2.4	-	-	-	-	-	
105-045	2435	-	-	-	1.8	0.3	0.6	0.2	0.5	0.2	-	4.5	0.0	-	2.7	77.0	0.2	0.9	-	0.0	0.0	0.1	0.8	-	6.8	0.0	-	-	-	-	0.0	-	0.6	2.5	-	-	-	0.2	
105-065	568	35	700	-	3.7	-	1.4	-	2.1	-	-	2.3	0.2	-	1.9	53.9	1.8	4.4	-	-	-	-	-	-	22.0	1.6	0.2	-	-	-	-	-	2.6	0.2	-	-	-	-	0.2
106-005	712	712	16200	0.3	-	-	-	-	2.0	1.4	-	6.2	2.5	-	2.2	48.5	13.7	3.4	3.1	8.7	1.1	-	-	-	4.8	-	-	-	-	-	-	0.6	-	1.4	-	-	-	0.3	
106-045	1319	264	4600	-	1.7	-	0.2	-	2.3	5.5	0.3	7.7	9.7	-	4.6	33.5	17.5	3.0	3.3	2.0	1.1	0.9	2.0	-	2.1	-	-	-	-	-	2.0	-	0.3	-	-	-	-	0.3	

Sample	Total Count	Theca/gr. sed.	Tint./gr. sed.	<i>Arcella vulgaris</i>	<i>C. aculeata</i> "aculeata"	<i>C. aculeata</i> "discoidea"	<i>C. aculeata</i> "ecornis"	<i>C. constricta</i>	<i>D. prol.</i> "protiaeformis"	<i>D. prol.</i> "elegans"	<i>D. prol.</i> "inflata"	<i>D. ampullula</i>	<i>D. fragosa</i> "fragosa"	<i>D. fragosa</i> "strain a"	<i>D. globulus</i>	<i>D. manicata</i>	<i>D. oblonga</i> "oblonga"	<i>D. oblonga</i> "lacustris"	<i>D. oblonga</i> "lanceolata"	<i>D. oblonga</i> "linearis"	<i>D. urceolata</i> "urceolata"	<i>D. urceolata</i> "amphora"	<i>D. urceolata</i> "lebes"	<i>D. urens</i>	<i>D. viscidula</i>	<i>L. vas</i>	<i>P. compressa</i>	<i>A. cyclostoma</i>	<i>C. corona</i>	<i>C. triacantha</i>	<i>H. sphagnum</i>	<i>L. spiralis</i>	<i>O. pyxys</i> sp.	<i>T. arcuata</i>	<i>C. arcelloides</i>	<i>P. acropodia</i>	<i>E. alveolata</i>		
106-085	601	301	4500	0.3	4.3	-	1.0	-	2.0	7.5	0.2	9.0	10.0	-	5.6	31.2	17.6	0.3	1.7	1.7	0.7	1.0	-	2.7	-	-	-	-	-	0.3	-	1.7	-	-	-	-	0.7	-	
106-125	620	248	2900	-	0.6	-	0.3	-	2.6	1.0	-	9.0	0.3	1.0	12.3	48.7	6.5	1.3	6.8	1.0	0.3	-	1.3	-	5.2	-	-	-	-	-	-	-	1.0	-	-	-	-	1.0	-
106-165	129	7	100	-	1.5	-	-	-	1.5	-	-	13.8	-	-	12.3	46.2	6.2	4.6	-	-	-	-	-	7.7	-	-	-	-	-	-	-	4.6	-	-	-	-	-	1.5	-
107-005	564	564	8000	-	1.1	-	1.4	-	1.1	2.1	0.4	5.3	8.9	-	3.9	35.8	16.3	3.5	4.3	4.6	1.8	0.7	1.1	0.4	3.9	-	-	-	-	1.1	0.7	0.7	-	-	-	-	-	1.1	-
107-045	661	661	29700	-	3.0	-	3.3	-	-	1.5	-	8.2	11.2	-	6.0	31.7	16.0	3.3	1.8	5.7	0.9	1.5	1.2	0.6	2.1	-	-	-	-	-	-	0.3	-	-	-	-	-	1.5	-
107-085	559	56	1700	0.4	4.7	-	4.3	-	2.1	2.0	0.9	6.5	25.1	-	6.1	22.2	12.2	1.4	1.1	3.2	-	1.4	0.4	1.4	-	-	-	-	-	-	-	0.7	2.9	-	-	-	0.7	-	
107-125	531	266	14500	-	4.9	-	5.7	0.4	3.0	3.4	1.1	13.2	9.8	0.4	7.5	26.0	10.6	1.1	0.4	0.8	0.4	1.5	2.6	0.4	3.4	-	-	-	-	1.1	0.4	0.8	-	-	-	-	0.8	0.4	
107-165	659	110	2500	0.3	7.3	0.3	8.5	0.9	0.3	0.3	-	9.7	-	-	14.3	30.7	5.5	0.3	-	1.2	-	0.6	0.9	-	7.3	-	-	-	-	-	-	0.3	8.2	-	0.3	-	0.3	2.4	-
110-005	937	49	1100	0.5	15.6	5.2	-	-	-	0.3	-	5.4	0.4	1.5	0.2	38.2	4.3	1.1	-	12.1	0.1	-	0.4	0.4	1.2	1.6	0.1	-	-	-	-	5.3	1.9	-	-	0.1	0.4	3.2	-
110-045	910	47	800	0.8	13.3	2.9	1.0	1.0	0.5	1.5	-	2.3	2.9	-	5.8	34.0	4.8	2.1	-	11.4	0.3	-	0.3	-	1.3	0.7	-	0.2	0.7	3.3	0.7	-	0.1	0.4	0.2	7.6	-		
110-085	1081	49	1900	1.0	16.4	2.9	0.3	0.9	0.6	1.2	-	3.7	1.9	0.1	5.1	32.7	3.9	2.0	-	10.5	0.2	0.2	1.6	0.1	3.7	0.9	0.3	0.9	0.3	1.1	2.5	-	0.2	-	0.6	4.1	-		
110-125	647	22	700	0.3	19.8	1.5	0.2	0.6	0.3	2.3	0.2	6.3	1.7	0.2	2.0	31.8	1.4	2.2	0.3	11.6	2.0	0.2	1.9	-	2.0	1.1	-	0.8	0.6	0.3	5.6	-	0.2	0.2	0.6	2.0	-		
110-165	502	19	100	2.2	28.1	3.8	0.2	1.6	-	1.2	-	12.0	0.2	0.4	3.8	22.9	0.2	1.8	-	1.2	0.2	-	3.0	-	3.2	-	-	1.4	-	0.6	7.8	-	-	0.2	4.0	0.2	-		
110-205	241	11	-	3.7	28.2	18.3	-	5.8	-	0.4	-	0.4	0.4	0.8	3.3	13.7	0.4	0.8	-	-	-	-	-	-	-	-	-	-	1.2	-	2.5	3.3	-	1.7	-	10.4	3.7	-	
113-005	605	242	980	-	15.2	14.5	9.2	2.0	0.7	-	-	1.7	-	-	9.6	15.8	4.3	1.3	-	13.5	-	0.3	-	-	0.3	-	-	-	-	-	-	2.0	3.3	-	1.3	-	2.3	2.6	-
113-045	609	244	550	-	11.1	9.2	4.9	1.3	0.3	0.7	-	2.3	-	0.3	9.5	24.3	6.2	1.0	2.3	15.7	-	-	0.3	-	0.3	-	-	-	-	-	-	3.9	1.6	-	1.0	-	1.0	2.6	-
113-085	502	167	530	0.8	14.3	5.2	11.1	0.4	0.8	0.4	-	1.2	-	-	11.1	18.3	10.3	0.8	-	13.1	0.4	-	-	0.4	-	-	-	-	-	-	-	1.2	2.4	-	-	-	1.2	6.7	-
113-125	561	140	180	-	11.4	1.4	8.2	0.4	1.1	-	-	2.8	0.4	-	19.2	21.4	5.7	1.4	-	8.2	-	1.1	0.4	-	1.1	-	-	-	-	-	-	-	11.0	-	-	1.1	3.9	-	
113-165	222	15	30	-	13.6	7.3	12.7	-	0.9	0.9	-	5.5	-	0.9	23.6	10.0	3.6	-	-	1.8	-	-	-	-	-	-	-	-	-	-	-	0.9	11.8	-	-	3.6	2.7	-	
113-205	168	11	-	-	19.0	1.2	14.3	-	-	1.2	-	1.2	-	4.8	22.6	9.5	-	-	-	-	-	1.2	-	-	-	-	-	-	-	-	-	-	7.1	-	-	10.7	7.1	-	
120-005	566	566	290	-	0.7	-	1.4	-	1.1	12.0	0.7	8.5	-	1.1	2.8	9.9	3.5	-	9.9	8.5	-	0.7	-	-	0.4	1.1	-	1.1	0.4	34.9	-	0.4	-	-	-	-	-	1.4	-
120-045	526	132	4110	-	2.3	0.4	3.0	-	-	2.1	0.2	7.2	0.4	0.8	26.5	17.4	10.2	-	0.8	17.8	-	-	-	0.4	0.8	0.4	-	0.8	-	4.9	1.1	-	-	-	-	0.4	1.9	0.4	
120-085	598	60	110	0.3	2.0	1.0	1.7	-	-	5.0	-	8.4	6.4	0.3	28.9	13.8	3.7	0.7	3.4	9.4	0.7	0.3	-	0.3	2.3	-	-	0.3	1.7	4.0	2.7	-	-	-	-	-	2.7	-	
120-125	568	57	40	-	3.2	0.4	-	-	-	6.2	0.2	11.3	3.5	1.4	26.4	11.3	10.6	0.4	3.2	13.7	0.7	-	1.4	0.7	-	-	-	0.4	0.7	-	1.4	-	0.7	-	-	-	2.5	-	
120-165	685	69	80	0.6	12.0	1.5	-	-	0.3	4.4	-	6.4	5.8	0.9	22.2	14.0	6.4	0.9	0.9	7.3	-	-	-	-	0.3	-	-	0.3	-	0.6	8.2	-	0.3	-	0.6	6.4	-		
122-005	1199	92	20	-	-	-	-	-	0.2	0.5	10.3	0.8	11.8	6.4	0.5	0.4	17.9	0.4	0.2	-	11.5	2.6	0.2	0.7	-	2.9	2.2	1.1	2.2	-	25.1	-	1.3	-	-	-	-	-	
122-045	678	42	710	-	-	-	-	-	0.4	5.5	8.7	0.4	6.6	3.5	2.2	0.9	2.7	1.8	-	-	7.1	0.4	-	6.2	3.5	0.4	-	10.6	0.9	36.7	-	0.9	-	-	-	-	0.4	-	
122-085	313	24	10	-	-	-	-	-	1.9	1.3	11.8	0.3	5.1	3.8	2.5	17.8	9.6	-	-	8.9	-	-	6.4	3.2	3.2	-	-	11.5	2.5	9.6	-	0.6	-	-	-	-	-		
122-125	568	40	40	-	-	-	-	-	2.1	-	13.9	0.5	5.6	4.2	1.8	17.6	7.4	-	-	7.0	0.4	-	8.8	3.2	6.3	-	-	7.0	2.1	1.8	1.1	-	-	-	-	8.8	-		
122-165	375	36	20	-	-	-	-	-	0.5	1.1	7.5	-	9.1	3.2	0.5	18.7	9.1	-	-	2.1	-	-	10.7	2.1	7.0	0.5	-	3.7	1.6	9.6	1.1	-	-	-	-	12.3	-		
122-205	147	10	10	1.4	-	-	-	-	-	2.7	-	11.0	4.1	2.7	31.5	15.1	-	-	1.4	1.4	1.4	-	2.7	4.1	1.4	-	-	4.1	-	1.4	-	-	-	-	-	13.7	-		
122-245	402	23	30	-	-	-	-	-	1.0	0.5	17.5	-	1.5	3.5	0.5	37.5	9.0	-	-	0.5	-	-	10.0	-	4.0	0.5	-	0.5	1.0	1.5	-	-	-	-	-	11.0	-		
122-285	384	26	20	-	0.5	-	-	-	1.0	-	11.7	0.3	8.3	3.1	2.1	38.5	10.4	-	-	0.5	-	-	6.3	1.6	3.1	-	-	-	0.5	2.1	-	-	-	-	-	9.9	-		
122-325	164	13	10	-	-	-	-	-	1.2	-	9.8	-	8.5	-	4.9	39.0	11.0	-	1.2	-	-	-	2.4	-	2.4	-	-	-	-	4.9	1.8	-	-	-	-	12.2	-		
122-365	72	4	-	-	8.3	45.8	-	-	-	-	-	4.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	12.5	-		
122-405	264	18	-	-	35.6	31.1	-	26.5	-	-	-	-	-	-	6.1	-	-	-	-	-	-	-	-	-	-	-	-	-	0.8	-	-	-	-	-	-	-	-	-	

Table 4-2: Mean percent abundance, associated standard deviation and range of percent abundance of diagnostic species for each thecamoebian assemblage.

Assemblage	Mean	St.dev.	Range
<i>Difflugia manicata</i> Assemblage (25 samples)			
<i>Difflugia manicata</i>	57.8	7.9	46.2 - 77.0
<i>Difflugia oblonga</i> "oblonga"	5.8	3.9	0.2 - 13.7
<i>Difflugia oblonga</i> "linearis"	2.9	2.8	0.0 - 8.7
<i>Difflugia viscidula</i>	6.0	5.6	1.2 - 22.0
<i>Centropyxis aculeata</i> "aculeata"	3.1	4.2	0.2 - 16.7
Mixed <i>Difflugia manicata</i> Assemblage (20 samples)			
<i>Difflugia manicata</i>	33.2	7.6	20.3 - 45.7
<i>Difflugia ampullula</i>	9.0	5.1	2.3 - 18.9
<i>Difflugia oblonga</i> "oblonga"	9.4	6.3	1.4 - 19.7
<i>Difflugia oblonga</i> "linearis"	6.1	5.7	0.1 - 20.3
<i>Difflugia fragosa</i>	5.5	6.0	0.0 - 25.1
<i>Difflugia viscidula</i>	2.4	1.7	0.3 - 7.3
<i>Difflugia globulus</i>	7.2	6.7	0.2 - 27.3
<i>Centropyxis aculeata</i> "aculeata"	7.0	6.5	0.3 - 19.8
Mixed <i>Centropyxis aculeata</i> Assemblage (8 samples)			
<i>Centropyxis aculeata</i> "aculeata"	17.6	6.9	11.1 - 28.2
<i>Centropyxis aculeata</i> "ecornis"	8.7	4.8	0.2 - 14.3
<i>Centropyxis aculeata</i> "discoides"	7.6	6.1	1.2 - 18.3
<i>Difflugia manicata</i>	17.0	5.7	9.5 - 24.3
<i>Difflugia globulus</i>	12.8	8.0	3.3 - 23.6
<i>Difflugia globulus</i> Assemblage (11 samples)			
<i>Difflugia globulus</i>	27.7	8.2	17.6 - 39.0
<i>Difflugia manicata</i>	11.6	3.1	7.4 - 17.4
<i>Difflugia ampullula</i>	7.5	2.8	1.5 - 11.3
<i>Difflugia oblonga</i> "linearis"	6.9	5.9	0.5 - 17.8
<i>Difflugia urceolata</i> "lebes"	6.8	3.3	2.4 - 10.7
<i>Cucurbitella tricuspis</i> Assemblage (3 samples)			
<i>Cucurbitella tricuspis</i>	32.2	6.2	25.1 - 36.7
<i>Difflugia globulus</i>	1.4	1.3	0.4 - 2.8
<i>Difflugia manicata</i>	10.1	7.6	2.7 - 17.9
<i>Centropyxis-Arcella</i> Assemblage (2 samples)			
<i>Arcella vulgaris</i>	22.0	19.3	8.3 - 35.6
<i>Centropyxis aculeata</i> "aculeata"	38.4	10.4	31.1 - 45.8
<i>Centropyxis aculeata</i> "ecornis"	13.3	18.7	0.0 - 26.5

Figure 4-1: Location map of core sites selected for thecamoebian analysis.

Figure 4-2: Lithologic column and abundance diagrams for important thecamoebian species in North Basin Core 103. Numeric values in the abundance diagrams refer to values too small to be shown graphically. Refer to Figure 4-6 for the lithologic legend; Dm = Diffflugia manicata Assemblage, MDm = Mixed Diffflugia manicata Assemblage, AU = Agassiz Unconformity.

Figure 4-3: Lithologic columns and distribution curves of important thecamoebian species in North Basin cores 104a and 105. Values for the number of thecamoebians and tintinids per gram of sediment are unavailable for the uppermost samples of Core 105, however both groups were relatively abundant within these sediments. Numeric values in the abundance diagrams refer to values too small to be shown graphically. Refer to Figure 4-6 for the lithologic legend; Dm = Diffflugia manicata Assemblage, MDm = Mixed Diffflugia manicata Assemblage, AU = Agassiz Unconformity.

Figure 4-4: Lithologic columns and distribution curves of important thecamoebian species in North Basin Cores 106 and 107. Refer to Figure 4-6 for the lithologic legend; Dm = Diffflugia manicata Assemblage, MDm = Mixed Diffflugia manicata Assemblage, AU = Agassiz Unconformity.

106

107

Figure 4-5: Lithologic columns and distribution curves of important thecamoebian species for cores 110a and 113a north and south of Narrows. Numeric values in the abundance diagrams refer to values too small to be shown graphically. Refer to Figure 4-6 for the lithologic legend; MDm = Mixed Diffflugia manicata Assemblage, MCa = Mixed Centropyxis aculeata Assemblage, AU = Agassiz Unconformity; Centropyxis includes all three strains.

110a

Water Depth: 11.3m

Thecamoebians
/gr. wet sed.

Tintinids
/gr. wet sed.

Diffugia
manicata

Diffugia
globulus

Centropyxis
aculeata

Diffugia
oblonga
"linearis"

Diffugia
oblonga
"oblonga"

113a

Water Depth: 9.8m

Thecamoebians
/gr. wet sed.

Tintinids
/gr. wet sed.

Diffugia
manicata

Diffugia
globulus

Centropyxis
aculeata

Diffugia
oblonga
"linearis"

Diffugia
oblonga
"oblonga"

Figure 4-6: Lithologic column and distribution curves for important thecamoebian species in Core 120 in the South Basin. Ct = Cucurbitella tricuspis Assemblage, Dg = Diffflugia globulus Assemblage, AU = Agassiz Unconformity; Centropyxis includes all three strains.

Figure 4-7: Lithologic column and distribution curves for important thecamoebian species in Core 122a from the South Basin. Numeric values in the abundance diagrams refer to values too small to be shown graphically. Refer to Figure 4-6 for the lithologic legend; Ct = Cucurbitella tricuspis Assemblage, Dg = Diffflugia globulus Assemblage, CA = Centropyxis-Arcella Assemblage, AU = Agassiz Unconformity; Centropyxis includes two strains (“aculeata” and “ecornis”).

Figure 4-8: Summary of the distribution of thecamoebian assemblages. Horizontal tick marks on the cores represent sampled intervals (at 40 cm intervals except in core 105 which is at 20 cm intervals). The dashed line correlates the Agassiz Unconformity. The AMS ^{14}C date was provided by Vance (1996) and the secular variation model age was provided by King and Gibson (written comm.).

N

S

North Basin

Narrows

South Basin

Figure 4-9: SEM images of selected thecamoebian taxa.

1. Diffflugia manicata lateral view, scale bar = 10 μm , Core 103 (5 cm).
2. Diffflugia ampullula lateral view, scale bar = 10 μm , Core 103 (165 cm).
3. Diffflugia fragosa lateral view, scale bar = 10 μm , Core 103 (245 cm).
4. Diffflugia protaeiformis "elegans" lateral view, scale bar = 10 μm , Core 103 (45 cm).
5. Diffflugia protaeiformis "protaeiformis" lateral view, scale bar = 10 μm , Core 103 (125 cm).
6. Diffflugia globulus lateral view, scale bar = 10 μm , Core 103 (85 cm).
7. Cucurbitella tricusps lateral view, scale bar = 10 μm , Core 122a (5 cm).
8. Diffflugia urceolata "urceolata" lateral view, scale bar = 100 μm , Core 103 (5 cm).
9. Diffflugia urceolata "lebes" lateral view, scale bar = 10 μm , Core 103 (205 cm).
10. Centropyxis aculeata "aculeata" lateral view, scale bar = 10 μm , Core 122a (405 cm).
11. Diffflugia viscidula lateral view, scale bar = 10 μm , Core 103 (5 cm).
12. Cucurbitella corona lateral view, scale bar = 100 μm , Core 103 (125 cm).
13. Cucurbitella corona apertural view, scale bar = 100 μm , Core 103 (125 cm).
14. Diffflugia oblonga "oblonga" lateral view, scale bar = 10 μm , Core 103 (45 cm).
15. Diffflugia oblonga "linearis" lateral view, scale bar = 10 μm , Core 103 (85 cm).
16. Diffflugia oblonga "lacustris" lateral view, scale bar = 10 μm , Core 103 (45 cm).
17. Lesquereusia spiralis lateral view, scale bar = 10 μm , Core 122 (5 cm).
18. Lagenodiffflugia vas lateral view, scale bar = 10 μm , Core 122 (5 cm).

CHAPTER 5.

SOURCES OF LEAD IN HOLOCENE LAKE WINNIPEG SEDIMENTS: EVIDENCE FROM STABLE LEAD ISOTOPIC ABUNDANCES

ABSTRACT

Stable lead isotope composition can yield information on sources of lead in lake sediments. In this reconnaissance study, stable lead isotopic compositions were determined for nitric acid-soluble and residual sediment fractions of sediment samples from a north-south transect of Lake Winnipeg. Results show that lead in Lake Winnipeg sediment is derived from natural as well as anthropogenic sources and both interbasinal and vertical variations in source material can be distinguished. The natural-source lead in Lake Winnipeg sediments is predominantly derived from the Superior Province (model age 2.5 Ga). The North Basin sediment is characterized by highly radiogenic acid-soluble lead and relatively non-radiogenic residual lead derived from high radiogenic lead/common lead Archean granitic rocks of the Superior Province. Lead in the South Basin sediments is largely derived from Paleozoic and Mesozoic sedimentary rocks; these sediments have a more radiogenic common lead component originally extracted from the Superior Province during deposition of the Paleozoic and Mesozoic rocks. Vertical variations in lead isotope composition indicate three phases of lead input in Lake Winnipeg: 1) highly radiogenic Lake Agassiz sedimentation, 2) relatively constant isotopic compositions of natural Lake Winnipeg sources, and 3) reduced isotopic ratios of acid-soluble anthropogenic lead. Specific sources of anthropogenic lead for Lake Winnipeg can not be determined with the present data since the anthropogenic isotopic composition is unknown.

INTRODUCTION

Lake Winnipeg is the eleventh largest lake in the world. Covering a surface area larger than Lake Ontario and only slightly smaller than Lake Erie, it is an important feature of the Canadian landscape. It is an integral part of the Nelson River drainage basin which extends from the Rocky Mountains to Hudson Bay. The lake is situated over the contact between the Archean Superior Province to the east, and Paleozoic carbonates and siliciclastics of the Williston Basin to the west (Figure 5-1) and is the largest of a group of lakes, including Lake Winnipegosis and Lake Manitoba, which are remnants of post-glacial Lake Agassiz. A constriction referred to as The Narrows divides the lake into two basins, the large North Basin (approximately 240 km by 100 km) and smaller South Basin (approximately 90 km by 40 km). These basins have relatively flat and shallow lakebeds with water depths averaging 9 m in the South Basin and 16 m in the North Basin (Canadian Hydrographic Service, 1981).

Seismostratigraphic analysis of the Lake Winnipeg Basin reveals that Paleozoic rock is truncated against a subsurface escarpment and buried under thick accumulations of Holocene sediment (Todd and Lewis, 1996). Two sequences are recognized within the Holocene sediments: the thick Lake Agassiz sequence overlain unconformably by a thinner Lake Winnipeg sequence. The lower sequence is characterized by firm, brownish grey to olive grey, silty clay rhythmites and banded silty clay with occasional dropstones and grit (Lewis and Todd, 1996). This sequence is interpreted as deposition in glacial Lake Agassiz, with the rhythmites resulting from seasonal variations. The upper sequence, which overlies an erosional contact (Agassiz Unconformity), is characterized by soft, dark olive grey, silt-clay mud with discontinuous bands of lighter grey mud and sand grains near the base. This sequence is the result of accumulation in modern Lake Winnipeg.

The water budget of Lake Winnipeg is supported by inflows from four major river systems: the Winnipeg River (mean monthly flow of $771 \text{ m}^3 \text{ s}^{-1}$), Saskatchewan River (mean monthly flow of $667 \text{ m}^3 \text{ s}^{-1}$), Red-Assiniboine rivers (mean monthly flow of 159

m^3s^{-1}), and Dauphin River (mean monthly flow of $57 \text{ m}^3\text{s}^{-1}$) and numerous other streams surrounding the lake (Lewis and Todd, 1996). Except for the Winnipeg River, which drains from the Superior Province, these major rivers drain areas of urbanization and agricultural activity to the south and west of the lake (Kling, 1996). The catchment of the latter three rivers encompasses the Paleozoic and Mesozoic sedimentary terrains of central Canada and the north central United States. Outflow from Lake Winnipeg is through the Nelson River at the north end of the lake.

Despite its importance, there has been a paucity of research on Lake Winnipeg. Other than limited limnological and land-based studies, the only major scientific effort was a chemical, physical and biological survey involving the collection of fifty bottom sediment grab samples and several short cores by the Freshwater Institute of Fisheries and Oceans Canada in 1969 (Kling, 1996; Brunskill and Graham, 1979). Due to the need for an enhanced understanding of the regional geological history, a multidisciplinary offshore survey of Lake Winnipeg was performed in 1994 by the Geological Survey of Canada (GSC) and Manitoba Energy and Mines (MEM). Financial support for this survey was provided by the GSC as well as Manitoba Hydro and Manitoba Sustainable Development Innovations Fund.

Lead Isotopes

There are four naturally occurring stable lead isotopes: ^{204}Pb , ^{206}Pb , ^{207}Pb and ^{208}Pb . Only ^{204}Pb is non-radiogenic and thus, can be treated as a reference isotope; the remaining three isotopes are daughter products of radioactive decay of ^{238}U , ^{235}U and ^{232}Th (Faure, 1986). A summary of the decay path followed by each of the radioactive isotopes is provided in Appendix 5-1.

Stable lead isotopic ratios depend on the age and original mineral composition of the source rock from which the lead is derived (Sturges and Barrie, 1989). Since ^{204}Pb is not derived from radioactive decay its abundance has not changed since the Earth formed;

however, radioactive decay of U and Th has continually produced ^{206}Pb , ^{207}Pb , and ^{208}Pb . Consequently, not only has the abundance of lead increased, but the isotopic composition of average Earth lead has become more enriched in the radiogenic isotopes through geologic time. Isotopic ratios are usually expressed as $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ but in environmental work $^{206}\text{Pb}/^{207}\text{Pb}$ is often used.

Common rocks, such as granites, contain minerals with sufficiently high U/Pb and Th/Pb ratios to cause measurable changes in their lead isotopic compositions over time. The lead isotopic ratios of these rocks will continue to evolve until the lead is removed from the U-, Th-bearing system; thus, lead extracted from very old granitic rock will have a more radiogenic isotopic composition than lead removed from the system early in the rock history. Other rocks and minerals have such low U/Pb and Th/Pb ratios that their lead isotopic composition has not changed appreciably since time of formation. Although U/Pb and Th/Pb ratios are altered by radioactive decay, a number of geologic processes can significantly fractionate the elements, including magma generation, metamorphism and weathering. The geologic processes may produce regional variations in the U/Pb and Th/Pb ratios that affect the isotopic evolution of lead.

Lead in lake sediments is derived from natural sources, such as mineral weathering and erosion, volcanic emissions and soil dust, and in more recent times from anthropogenic emissions, primarily smelting, iron and steel manufacture, fossil fuel combustion, and the release of municipal and industrial effluents (Nriagu and Pacyna, 1988; Pacyna et al., 1991; Gobeil et al., 1995). Although pre-industrial anthropogenic sources have been documented (Renberg et al., 1994) most contributions have occurred since the mid-nineteenth century with combustion of leaded gasoline being the most significant (Graney et al., 1995).

A wide variety of studies, including surveys of sediments from the St. Lawrence Estuary and the Great Lakes (Gobeil et al., 1995; Graney et al., 1995), aerosols from the Great Lakes and rural Eastern Canada (Sturges and Barrie, 1987; 1989), and water samples

from coastal regions of British Columbia and the Great Lakes (Stukas and Wong, 1981; Flegal et al., 1989) have used stable lead isotopic ratios to trace the origin of anthropogenic lead inputs. This is possible because the isotopic ratios of lead are not fractionated by normal chemical and physical processes; lead released to the environment retains the isotopic composition of the source from which it was derived (Sturges and Barrie, 1989). This approach has generally been successful in identifying local sources of pollution. Sturges and Barrie (1987) suggested that the observed differences in $^{206}\text{Pb}/^{207}\text{Pb}$ ratios from urban Canada and the United States are the result of the different isotopic compositions of the lead used by Canadian and American companies in producing their leaded gasoline.

The aim of this reconnaissance study was to document spatial, temporal and compositional variations in the stable lead isotopic signatures from Holocene sediments of Lake Winnipeg. This geologically unique location, overlying the boundary between Archean and Paleozoic bedrock, makes it possible to assess the influence of these two distinctly different sources on the isotopic composition of the lake sediments. In addition, more recent sediments were examined for evidence of anthropogenic lead sources.

MATERIALS AND METHODS

Several gravity/piston cores and box cores were collected from Lake Winnipeg during a GSC cruise (designated Namao 94-900) in August 1994. Following core recovery the gravity/piston core liners were cut in 1.5 m sections, sealed and stored upright in a core cooler. Box cores were subsampled using a vacuum pump to force a 10 cm core liner into the sediment; the short cores were then subdivided into 1cm slices aboard ship. The box core samples were collected in order to determine trace metal content and isotopic composition, thus great care was taken to avoid contamination, especially from atmospheric sources.

Three box cores (approximately 40 cm in length) and two gravity cores (Core 103 = 816 cm and Core 122a = 472 cm in length) were sampled for stable lead isotope analysis (Figure 5-1). Selection of one gravity core and one box core from each basin and an additional box core from The Narrows provides a north-south transect of Lake Winnipeg. Box cores were subsampled at sediment depths of 1, 12, 28 and 40 cm and gravity cores were subsampled at 120 cm intervals, providing a total of 24 samples.

In order to investigate sources of lead input to sediment of Lake Winnipeg a procedure was needed to extract the labile component from the total lead. Sequential chemical extractions have been developed for partitioning trace metal components into five fractions operationally defined as: exchangeable, carbonate-bound, Mn and Fe oxide-bound, bound to organic matter and residual (Tessier et al., 1979). However, since the majority of lead in the freshwater environment, including the anthropogenic component, is associated with organic matter through bioaccumulation or adsorption by humic substances (Jaworski, 1987), a simpler method of extraction was chosen. A dilute acid leach dissolves lead bound to organic material and ferromanganese oxides leaving the residual lead bound to the mineral structure (Shirahata et al., 1980). Graney et al. (1995) tested several acid leaches and found negligible differences in concentrations and isotopic ratios obtained from lead extracted by various HCl and/or HNO₃ strengths. For the present study 3 N HNO₃ was chosen.

All sample preparation was done in a laminar flow fume hood in a clean lab. Approximately 100 mg of air-dried sample was mixed with 4 ml of 3N HNO₃ in a 15 ml Teflon beaker and warmed on a hot plate for 15 minutes. The capped beakers were then placed in an ultrasonic bath for 30 minutes to aid disaggregation of clay-rich sediments. After several hours the solvent was separated from the residual sediment using a micropipette, and dried in a Teflon beaker. The residue was rinsed with water (twice) to remove any remaining solvent then dissolved in a series of strong acids: 0.5 ml 12N HNO₃ and 2 ml HF; 2 ml 8N HNO₃; then 2 ml 6N HCl. The lead was separated from other

elements by a sequential HCl-HBr ion-exchange column with AG-1-X8 anion exchange resin. Blanks for laboratory procedures are typically less than 100 pg and therefore are negligible. Isotopic ratios were measured on a Finnigan-MAT 261 multicollector thermal ionization mass spectrometer using a single Re filament and silica gel and phosphoric acid. The measured ratios were corrected for fractionation; the correction factors (Appendix 5-2) were determined by repeated analysis of the NBS 981 standard.

RESULTS AND DISCUSSION

Bedrock geology around Lake Winnipeg varies significantly from east to west in both rock type and age (Figure 5-1). The rates and products of erosion differ according to the rock type, affecting the concentration and isotopic composition of lead incorporated into the lake sediments. Granites and granitic gneisses are enriched in U, Th and Pb while carbonates and siliciclastics contain lower concentrations of these elements (Faure, 1986); thus the old silica-rich rocks of the Superior Province have a greater potential to enrich the sediments with lead than do the Paleozoic sedimentary rocks to the west. This high availability of lead in the Precambrian rocks, however, is balanced by the slow rates of erosion and low sediment loads carried by rivers draining shield areas (Brunskill and Graham, 1979).

Bulk sediment lead concentrations in core and grab samples from Lake Winnipeg reveal a north to south increase in the amount of lead (Henderson, 1996; Lockhart, 1996). The lead enrichment of surface samples in the South Basin has been attributed to anthropogenic input; however, this fails to explain the lead enrichment at depth in the sediment cores. Postdepositional remobilization and redistribution of lead in lacustrine sediments is believed to represent only a small proportion (< 4%) of the total lead abundance (Gobeil and Silverberg, 1989). Thus, the north to south trend is probably the result of variations in the drainage systems feeding the two basins. The North Basin is supported by the Saskatchewan and Dauphin Rivers to the west and numerous small rivers

to the east. Both of the western rivers flow through extensive lake systems before they reach Lake Winnipeg; for example, much of the sediment load from the Saskatchewan River is deposited in Cedar and Moose lakes (Brunskill and Graham, 1979). Retention of lead in a lake is virtually complete due to the low particle reactivity of this element (Blais and Kalff, 1993). Thus most of the lead carried by the large western rivers probably never reaches Lake Winnipeg. The South Basin receives most of its input from the Red and Winnipeg Rivers; neither of these flow through lake systems.

The stable lead isotope ratios (reported as $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{207}\text{Pb}$) of acid-soluble lead and the residual sediment measured in this study are presented in Table 5-1 and Figures 5-2 and 5-3. When the isotopic ratios ($^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$) are plotted against $^{206}\text{Pb}/^{204}\text{Pb}$, the points essentially fall on a straight line (Figure 5-2). This line represents the mixing line of acid-soluble and residual sediment samples. Generally the residual sediment samples fall within a tight group with relatively low isotopic ratios while the acid-soluble leads tend to be dispersed along the mixing line towards more radiogenic values.

In Lake Winnipeg sediments, the acid-soluble leads are much more radiogenic than those of the residual sediments (Table 5-1 and Figures 5-2 and 5-3) suggesting that radiogenic lead is preferentially weathered as a result of partial decomposition of the source material. This has been shown to be the case both experimentally and through the study of geological examples. The isotopic composition of lead derived from complete rock dissolution would reflect the U/Th/Pb abundances of the original minerals and subsequent radioactive decay of Th and U. However, leaching experiments on metamict mineral phases revealed preferential release of radiogenic lead from radiation-damaged sites (Gariépy et al., 1990). Stern et al. (1966) estimated that up to 85% of the radiogenic lead was lost as a result of chemical weathering of zircons from gneiss. Work by Hart and Tilton (1966) on sediments from Lake Superior illustrated that the lead isotopic compositions of the acid leach and water leach fractions were more radiogenic than the lead

in the bulk sediment (Table 5-2). An investigation of the lead isotopic composition of a mountain stream draining granodiorite bedrock in California illustrated that the lead isotope ratios in the streamwater were much more radiogenic than those measured for the whole rock but were essentially the same as lead extracted by a weak acid leach (Erel et al., 1991).

Within the residual lead fraction, the four samples from Core 113b cluster in a small group distinct from the other residual lead samples. On a $^{206}\text{Pb}/^{204}\text{Pb}$ - $^{208}\text{Pb}/^{204}\text{Pb}$ plot for the residual fraction (Figure 5-4), Core 113b samples appear to represent a different slope ($m = 1.97$) than the remaining samples ($m = 1.03$). This perhaps indicates the influence of a localized sediment source from the small stream draining the Superior Province to the southeast. Core 113b is the only core taken in close proximity to shore and therefore, the location most likely to experience the influence of a local source. A localized Superior Province sediment source is also consistent with the low $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios observed in Core 113b residual sediments (Figure 5-4) since the lead contained in the residual component is probably common lead characteristic of the Precambrian. Isotopic ratios ($^{206}\text{Pb}/^{204}\text{Pb}$ - $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ - $^{208}\text{Pb}/^{204}\text{Pb}$) for the acid-soluble lead fraction of Core 113b samples are colinear with other acid-soluble lead samples (Figure 5-2), thus this component appears to be more pervasive. This is to be expected due to the fact that the acid-soluble fraction represents the more labile portion of lead (Graney et al., 1995).

Pending completion of concentration measurements for acid-soluble and residual lead fractions the assumption was made that the abundance of lead in the acid-soluble component is far greater than that of the residual component. This assumption is quite reasonable based on concentration measurements of sequential extraction components made by other workers (Tessier et al., 1979; Graney et al., 1995). Both acid-soluble and residual leads lie along a straight line in coordinates of $^{206}\text{Pb}/^{204}\text{Pb}$ - $^{207}\text{Pb}/^{204}\text{Pb}$; in view of the disparate allotment of lead this may be due to unleached acid-soluble lead contamination

of the residual lead component. However, isotopic compositions are internally consistent therefore, this is probably not a significant problem.

It is more likely that lead in the residual and acid-soluble components were originally derived from the same source rocks. The slope of the regression line ($m = 0.165$) of the $^{206}\text{Pb}/^{204}\text{Pb} - ^{207}\text{Pb}/^{204}\text{Pb}$ data indicates a model age of the original source rock of 2.5 Ga (Faure, 1986), thus suggesting the lead in Lake Winnipeg sediments is predominantly derived from the Superior Province. This regression line intersects the Stacey-Krammers Model growth curve at 2.5 Ga (Figure 5.5) indicating that the original source represented average crustal lead.

Isotopic ratios suggest that the acid-soluble lead tends to be more radiogenic towards the north (Figure 5-3). As discussed earlier, the concentration of lead is lower in the North Basin than in the South Basin; this is presumed to be due to lack of lead input from the major rivers to the west. If this is the case then the majority of lead comes from small rivers draining Shield rocks to the east; thus, the sediments of the North Basin would be strongly influenced by Archean bedrock. The isotopic compositions of acid-soluble lead are comparable with acid leach results of Quaternary lake sediments from other Canadian Shield localities, suggesting that the Precambrian source material has a strong influence on the isotopic ratios (Table 5-2; Chow, 1965; Hart and Tilton, 1966; Doe, 1970).

The mineralogy and great age of these source materials suggest that the small amount of sediment derived from these resistant rocks would be enriched in radiogenic lead. Growth curves of lead in average continental crust indicate that the $^{206}\text{Pb}/^{204}\text{Pb}$ ratio of common lead in Superior Province (Archean) rocks should have values of about 13 to 13.5 (Faure, 1986). However, Superior Province rocks are dominated by granites and gneisses which generally have higher U/Pb and Th/Pb ratios than the Paleozoic carbonates and siliciclastics. Since Superior rocks are very old, the ratio of radiogenic lead/common lead for these Archean rocks is relatively high; consequently, lead eroded recently from the Superior Province would have a highly radiogenic isotopic composition.

Towards the south the source of lead becomes dominated by the Red-Assiniboine River; this river system draws its sediment supply from Paleozoic and Mesozoic carbonates and siliciclastics. The Winnipeg River supplies a negligible amount of sediment to the South Basin for although its annual discharge is 4 to 10 times greater than the Red River, the sediment load is reduced due to its Precambrian shield watershed (Brunskill and Graham, 1979). Since carbonates and siliciclastics generally have lower U/Pb and Th/Pb ratios (Faure, 1986) and the rocks are much younger, it is likely that less radiogenic lead has been produced in these rocks since deposition; consequently the ratio of radiogenic lead/common lead is lower. Thus, the isotopic composition of acid-soluble lead in the South Basin has a less radiogenic signature than the acid-soluble lead of the North Basin.

The isotopic ratios of residual lead shows the opposite trend to that of the acid-soluble lead; residual lead of the South Basin is characterized by higher $^{206}\text{Pb}/^{207}\text{Pb}$ ratio than that of the North Basin. In Paleozoic rocks, the common lead isotopic composition is more radiogenic with $^{206}\text{Pb}/^{204}\text{Pb}$ values of about 17.5 to 18. This high ratio common lead component is not preferentially weathered from the Paleozoic rock as the radiogenic lead is preferentially extracted. Thus the residual lead components tend to reflect the composition of the common lead component.

Vertical variations in the stable lead isotope signatures can be used to divide the core into sections: the Lake Agassiz, the lower Lake Winnipeg and the anthropogenic phases (Figure 5-3). The lowermost section, corresponding to the post-glacial Lake Agassiz sequence, is based on two samples, one from the North Basin and one from the South Basin. From these limited data, the Lake Agassiz sediments appear to be characterized by lead which is more radiogenic than the overlying Lake Winnipeg sequence. This may indicate a postglacial increase in the supply of Precambrian sediment. The Wisconsinan ice sheets eroded and entrained large amounts of material as they advanced across the Precambrian Shield and after ice retreat this sediment was released resulting in large volumes of unconsolidated Precambrian detritus.

The lower Lake Winnipeg sediments are characterized by relatively constant lead isotope compositions at each location (Figure 5-3). These isotopic signatures represent the natural post-Agassiz source of lead to Lake Winnipeg sediments and indicates that these sources remained virtually unchanged for several thousand years.

In the most recent Lake Winnipeg sediments the isotopic ratio of acid-soluble lead is significantly reduced (Figure 5-3). This is interpreted as the result of the addition of lead from anthropogenic sources. Prior to the advent of unleaded gasoline, the dominant source of anthropogenic lead emissions was the combustion of gasoline, contributing up to 76% of total anthropogenic lead (Pacyna et al., 1991). $^{206}\text{Pb}/^{207}\text{Pb}$ ratios for typical leaded gasolines range from 1.06 to 1.20 (Chow and Johnstone, 1965; Farmer et al., 1996). These ratios are significantly lower than the natural post-Agassiz lead sources thus supporting the contention that the relatively non-radiogenic isotopic composition of the acid-soluble lead in upper samples is due to anthropogenic input. The specific anthropogenic sources responsible for the modern lead isotope composition cannot be determined from the available data. The acid-soluble component consists of lead from natural and anthropogenic sources in unknown proportions; therefore, the precise isotopic composition of the anthropogenic lead is not known.

The possible anthropogenic influence is quite evident in the upper two samples (1 and 12 cm) in each box core and in the surface sample of Core 122a; however, it is not apparent in the surface sample of Core 103 where there is only a slight reduction in the isotopic ratios. This is consistent with ^{210}Pb , which was detected at 5 and 15 cm in Core 122a but only in the top 5 cm in Core 103 (Lockhart, 1996). ^{210}Pb (half-life 22.4 years), produced by the decay of an isotope of the gas radon (^{222}Rn), is deposited from the atmosphere; once incorporated into the sediment its activity decreases as a function of time (Dörr et al., 1991). The limit for ^{210}Pb is about 150 years (Lockhart, 1996).

Pollen diagrams from southwest Manitoba and Koores Lake, Minnesota show an increase in weed pollen such as Ambrosia (ragweed) pollen and Chenopodiineae in the

upper 30-50 cm (Ritchie and Yarranton, 1978; McAndrews, 1988). The increased abundance of these particular weed pollen is associated with early European settlement in south central Canada and usually indicates the start of anthropogenic perturbation of the sediment record. Results from this study indicate that reduction in lead isotope composition corresponds to anthropogenic influence as indicated by the regional pollen records.

CONCLUSIONS

This study indicates that lead of Lake Winnipeg sediment is derived from natural as well as anthropogenic sources. The natural-source lead in Lake Winnipeg sediments is predominantly derived from the Superior Province (model age 2.5 Ga); however, interbasinal variations in isotopic composition of acid-soluble and residual components indicate that some lead experienced a complex depositional history. The North Basin receives much of its lead directly from high radiogenic lead/common lead rocks of the Superior Province. These sediments are characterized by a highly radiogenic acid-soluble lead component and a relatively non-radiogenic residual lead. In the South Basin sediment, lead is largely derived from Paleozoic and Mesozoic carbonates and siliciclastics with low radiogenic lead/common lead ratios. The common lead component of the Paleozoic and Mesozoic rocks was originally extracted from Superior Province rocks then later eroded from these rocks and deposited in Lake Winnipeg sediment. As a result the residual sediment fraction of the South Basin is characterized by a higher (more radiogenic) lead isotopic composition.

Vertical variations in lead isotope composition of the acid-soluble component indicate the most recent sediments are strongly influenced by anthropogenic sources. These most recent sediments are characterized by lower isotopic compositions in the acid-soluble lead. Specific sources of anthropogenic lead for Lake Winnipeg can not be determined with the present data since the anthropogenic isotopic composition is unknown.

Table 5-1: Isotopic compositions of acid-soluble and residual lead.

Acid-Soluble

Sample	206/204 _{corr}	207/204 _{corr}	208/204 _{corr}	206/207
Core 103				
0	23.90	16.42	43.46	1.46
120	24.07	16.45	43.70	1.46
240	24.31	16.47	43.85	1.48
360	24.42	16.48	44.00	1.48
480	24.43	16.47	44.01	1.48
600	23.72	16.35	43.31	1.45
720	25.17	16.45	44.85	1.53
Core 108				
1	22.17	16.17	41.79	1.37
12	23.45	16.42	43.17	1.43
28	24.05	16.47	43.86	1.46
40	24.17	16.51	43.88	1.46
Core 113b				
1	21.96	16.13	41.56	1.36
12	21.90	16.13	41.46	1.36
28	22.78	16.24	42.34	1.40
40	22.98	16.29	42.52	1.41
Core 117				
1	20.38	15.88	40.05	1.28
12	20.22	15.86	39.86	1.28
28	21.33	16.01	41.01	1.33
40	21.17	15.96	40.87	1.33
Core 122a				
0	19.92	15.81	39.55	1.26
120	20.98	15.94	40.60	1.32
240	21.50	16.01	41.04	1.34
360	21.79	16.05	41.29	1.36
460	23.25	16.29	42.61	1.43

Residual sediments

Sample	206/204 _{corr}	207/204 _{corr}	208/204 _{corr}	206/207
Core 103				
0	18.16	15.45	38.01	1.18
120	17.84	15.41	37.58	1.16
240	17.85	15.41	37.65	1.16
360	17.53	15.36	37.35	1.14
480	17.39	15.34	37.24	1.13
600	17.58	15.37	37.45	1.14
720	18.47	15.53	38.28	1.19
Core 108				
1	17.58	15.38	37.35	1.14
12	17.60	15.36	37.38	1.15
28	16.95	15.27	36.47	1.11
40	17.75	15.50	37.72	1.14
Core 113b				
1	16.86	15.25	36.34	1.11
12	16.83	15.24	36.27	1.10
28	16.78	15.23	36.22	1.10
40	16.91	15.25	36.47	1.11
Core 117				
1	18.30	15.50	38.05	1.18
12	18.54	15.51	38.30	1.20
28	18.51	15.52	38.26	1.19
40	18.25	15.48	37.84	1.18
Core 122a				
0	18.79	15.57	38.59	1.21
120	18.77	15.56	38.55	1.21
240	18.57	15.51	38.32	1.20
360	18.47	15.51	38.28	1.19
460	18.48	15.51	38.42	1.19

Table 5-2: Isotopic composition of lead in Quaternary lake sediments from adjacent drainage systems of the Canadian Shield. Most values represent acid-soluble lead components, those marked with asterisks represent samples which are not acid-soluble sediment fractions: * water-soluble leach, ** bulk sediment lead composition. Sources: 1. Doe, 1970; 2. Chow, 1965; 3. Hart and Tilton, 1966.

Locality	Source	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
Hudson Bay, Canada	1,2	25.00	16.41	46.83
	1,2	24.39	16.34	46.54
	1,2	24.15	16.28	45.90
	1,2	23.42	16.23	45.04
	1,2	23.49	16.35	45.01
	1,2	22.36	16.17	44.66
	1,2	22.07	16.12	42.71
	1,2	21.63	16.00	43.37
Great Slave Lake, Canada	1,2	23.41	16.38	49.33
	1,2	20.99	15.97	40.69
Great Bear Lake, Canada	1,2	24.15	16.59	44.10
	1,2	22.08	16.18	42.13
	1,2	21.56	16.13	41.77
	1,2	21.46	16.15	41.37
Lake Superior, North America	1,3	22.84	16.34	42.86
	1,3	22.48*	16.20*	42.34*
	1,3	20.53**	15.87**	40.34**

Figure 5-1: Location map showing sample locations for lead analyses and generalized bedrock geology (modified after Todd, 1996 and Teller and Bluemle, 1983).

Figure 5-2: Plot of $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ for all Lake Winnipeg samples. Solid symbols represent the acid-soluble fraction and open symbols represent the corresponding residual sediments.

Figure 5-3: Distribution of $^{206}\text{Pb}/^{207}\text{Pb}$ with depth. Solid symbols represent the acid-leached fraction and open symbols represent the corresponding residual sediments. AU indicates the depth of the Agassiz unconformity. The age of the unconformity is 7300 B.P. in Core 103 (geomagnetic secular variation age; King and Gibson, written comm.) and 4040 B.P. (AMS radiocarbon date; Vance, 1996)

Figure 5-4: Plot of $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ for residual sediments.

On the $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ the regression line for all residual sediment samples is shown in black, the regression line for Core 113b samples is shown in green and the regression line for samples from the other four cores is shown in purple.

Figure 5-5: Plot of $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$ for all Lake Winnipeg samples showing the Stacey-Krammers Model growth curve. The regression line of acid-soluble (+) and residual (O) leads has a slope of 0.165. Solid dots (•) represent isotopic compositions at 0.5 Ga intervals for the Stacey-Krammers Model.

CHAPTER 6.

CONCLUSIONS

This study has illustrated that thecamoebians can play an important role in deciphering the paleolimnological history of Lake Winnipeg. It appears from this study that biologic productivity and consequently the composition of organic material in the sediments acting as food sources are the main controls on thecamoebian taxa in Lake Winnipeg. Other factors controlling the distribution of thecamoebian distribution are water chemistry and turbidity. Inorganic sediment geochemistry and water temperature do not appear to be significant considerations. Climate may indirectly affect the thecamoebian distribution by influencing the lake catchment, thus controlling factors such as nutrient inflow.

Tests of Lake Winnipeg thecamoebians are generally small; usually they are at the lower size range limit known for each group. Test size is the result of food availability and the feeding period prior to asexual fission (Medioli et al., 1990). If thecamoebians replicate often without extended feeding periods between generations, the test will most likely be small; thus it appears that Lake Winnipeg is a very productive lake.

Conclusions about the paleoenvironmental significance of some key thecamoebian taxa can be made on the basis of their distribution in Lake Winnipeg sediments.

Cucurbitella tricuspis is indicative of recent eutrophication of the South Basin. There is no evidence from this study that Diffflugia globulus is a cold climate (arctic) indicator species, as others have suggested. The species Centropyxis aculeata and Arcella vulgaris which dominate the earliest South Basin sediments, tolerate hyposaline conditions. In The Narrows, where Centropyxis aculeata dominates a mixed association of diffugiids, the expansion of this species is related to harsh conditions created by decreased algal food source and increased water turbulence. Diffflugia oblonga, a species which is ubiquitous whenever the sediments are sufficiently organic, is present but never dominates the fauna as is the case in other studies. This is probably because gyttja, the optimum substrate for

this species, has not developed in Lake Winnipeg. In the North Basin, Diffflugia manicata is dominant throughout the Lake Winnipeg sequence indicating that this part of the lake has remained relatively unchanged since the retreat of Lake Agassiz. The abundance of Diffflugia manicata in the North Basin is probably related to acceptance by this taxon of cyanophyta as its food source.

Stable lead isotope composition can yield information on sources of lead in lake sediments. The lead isotopic composition of Lake Winnipeg sediment indicates lead is derived from natural as well as anthropogenic sources. The natural-source lead in Lake Winnipeg sediments is predominantly derived from the Superior Province (model age 2.5 Ga); however, interbasinal variations in isotopic composition of acid-soluble and residual components indicates that some lead experienced a complex depositional history. The North Basin receives much of its lead directly from high radiogenic lead/common lead rocks of the Superior Province. In the South Basin sediment, lead is largely derived from Paleozoic and Mesozoic carbonates and siliciclastics with low radiogenic lead/common lead ratios. The common lead component of the Paleozoic and Mesozoic rocks was originally extracted from Superior Province rocks then later eroded from these rocks and deposited in Lake Winnipeg sediment.

Vertical variations in lead isotope composition of the acid-soluble component suggests the most recent sediments are strongly influenced by anthropogenic sources. These most recent sediments are characterized by lower isotopic compositions of acid-soluble lead. Specific sources of anthropogenic lead for Lake Winnipeg can not be determined with the present data since the anthropogenic isotopic composition is unknown.

This reconnaissance study of stable lead isotopic compositions of acid-soluble and residual sediment fractions illustrates that significant information can be obtained from the lead isotopes, however, a more comprehensive study is required.

REFERENCES

- ARCHER, W., 1866. (No title). Quarterly Journal of Microscopical Science, 6: 185-188.
- ASIOLI, A., MEDIOLI, F.S. AND PATTERSON, R.T., 1996. Thecamoebians as a tool for reconstruction of paleoenvironments in some Italian lakes in the foothills of the Southern Alps (Orta, Varese and Candia). Journal of Foraminiferal Research, 26: 248-263.
- AVERINTZEV, S.V., 1906. Rhizopoda prêsnykh vod. Imperatorskoe Sankt-Peterburgskoe Obshchestvo Estestvoispytatelei Trudy, 36 (2), 346 p.
- BAJKOV, A., 1930. Biological conditions of Manitoba lakes. Contributions to Canadian Biology and Fisheries, 5: 383-422.
- BAJKOV, A., 1934. The plankton of Lake Winnipeg drainage system. Internationale Revue der Gesamten Hydrobiologie und Hydrographie, 31: 239-272.
- BEYENS L., CHARDEZ, D. AND DEBAERE, D., 1991. Ecology of aquatic testate amoebae in coastal lowlands of Devon Island (Canadian High Arctic). Archiv für Protistenkunde, 140: 23-33.
- BEZYS, R.K., 1996. Paleozoic geology of the Lake Winnipeg area and repositioning of the Precambrian-Paleozoic boundary. In Todd, B.J., Lewis, C.F.M., Thorleifson, L.H., and Neilsen, E. (eds.), Lake Winnipeg Project: Cruise Report and Scientific Results, Geological Survey of Canada Open File 3113, p. 127-139.

- BLAIS, J.M., AND KALFF, J., 1993. Atmospheric loading of Zn, Cu, Ni, Cr, and Pb to lake sediments: The role of catchment, lake morphometry, and physio-chemical properties of the elements. *Biogeochemistry*, 23:1-22.
- BONNET, L., 1959. Dékystement, phase trophique et enkystement chez Plagiopyxis minuta Bonnet (Thécamoebiens), Incidences systématiques. *Comptes Rendus de l'Académie des Sciences de Paris*, 249: 2617-2619.
- BONNET, L., 1964. Le peuplement thécamoebien des sols. *Rev. Ecol. Biol. Sol.* 1: 123-408.
- BRUNSKILL, G.J., AND GRAHAM, B.W., 1979. The offshore sediments of Lake Winnipeg. Fisheries and Marine Services Manuscript Report, v. 1540, 75 p.
- BRUNSKILL, G.J., SCHINDLER, D.W., ELLIOTT, S.E.M. AND CAMPBELL, P., 1979a. The attenuation of light in Lake Winnipeg waters. Canadian Fisheries and Marine Service Manuscript Report 1522, 75 p.
- BRUNSKILL, G.J., CAMPBELL, P. AND ELLIOTT, S.E.M., 1979b. Temperature, oxygen, conductance and dissolved major elements in Lake Winnipeg. Canadian Fisheries and Marine Service Manuscript Report 1526, 127 p.
- BRUNSKILL, G.J., ELLIOTT, S.E.M. AND CAMPBELL, P., 1980. Morphometry, hydrology, watershed data pertinent to the limnology of Lake Winnipeg. Canadian Fisheries and Marine Service Manuscript Report , 37 p.

- BUHAY, W.M., 1996. Stable isotopic composition of pore water and organic matter from Lake Winnipeg sediments. In Todd, B.J., Lewis, C.F., Thorleifson, L.H. and Nielsen, E. (eds) Lake Winnipeg Project: Cruise Report and Scientific Results. GSC Open File 3113, p. 253-259.
- BURBIDGE, S.M. AND SCHRÖDER-ADAMS, C.J., in press. Thecamoebians in Lake Winnipeg: a tool for Holocene paleolimnology. *Journal of Paleolimnology*.
- BÜTSCHLI, O., 1880. Protozoa. In Bronn's Klassen und Ordnungen des Thier-Reichs. I Band, I Abth, p.1-224.
- CANADIAN HYDROGRAPHIC SERVICE, 1981. Observation Point to Grindstone Point, Chart 6258; scale 1:480 000.
- CARPENTER, W.B., 1861. On the Systematic Arrangement of the Rhizopoda. *Natural History Review*, 1: 456-472.
- CARTER, H.J., 1856. Notes on the freshwater Infusoria of the Island of Bombay. *Annals and Magazine of Natural History*, 18: 221-249.
- CARTER, H.J., 1864. On freshwater Rhizopoda of England and India. *Annals and Magazine of Natural History*, 13: 18-39.
- CASH, J., AND HOPKINSON, J., 1905. The British freshwater Rhizopoda and Heliozoa, vol. 1: Rhizopoda, Part 1. Ray Society, London, 151 p.

CASH, J., AND HOPKINSON, J., 1909. The British freshwater Rhizopoda and Heliozoa, vol. 2: Rhizopoda, Part 2. Ray Society, London, 166 p.

CHOW, T.J., 1965. Radiogenic leads of the Canadian and Baltic Shield regions. Symposium on Marine Geochemistry, 1964. Rhode Island University Narragansett Marine Lab. Occasional Publication, v. 3, 169-184 p.

CHOW, T.J. AND JOHNSTONE, M.S., 1965. Lead isotopes in gasoline and aerosols of Los Angeles basin, California. *Science*, 147: 551-552.

CLAPARÈDE, E., AND LACHMANN, J., 1859. Études sur les Infusoires et les rhizopodes, Tome I [2me partie]. Mémoires de l'Institut National Genevois, 6 (for 1858): 261-482.

CLAYTON, L., 1983. Chronology of Lake Agassiz drainage to Lake Superior. In Teller, J.T. and Clayton, L. (eds.) Geological Association of Canada Special Paper 26, p. 291-308.

COLLINS E.S., MCCARTHY, R.M., MEDIOLI, F.S., SCOTT, D.B. AND HONIG, C.A., 1990. Biogeographic distribution of modern thecamoebians in a transect along the eastern North American coast. In Hemleben, C., Kaminski, M.A., Kuhnt, W. and Scott, D.B., (eds.), Paleoecology, Biostratigraphy, Paleooceanography and Taxonomy of Agglutinated Foraminifera: NATO Adv. Study Inst. Series C, Math. and Phy. Sci. 327, p. 783-791.

- CROWE, J.M.E., 1973. Limnology of the South Basin of Lake Winnipeg, March 1965-March 1969. Manitoba Department of Mines and Environmental Management, Research Branch Manuscript Report No.73-24, 37 p.
- DEFLANDRE, G., 1929. Le genre Centropyxis Stein. Archiv für Protistenkunde, 67: 322-375.
- DEFLANDRE, G., 1953. Ordres des Testaceolobosa (De Saedeleer, 1934), Testaceofilosa (De Saedeleer, 1934), Thalamia (Haeckel, 1862) ou Thécamoebians (Auct.)(Rhizopoda Testacea). In Grassé, P. P. (ed.), Traité de Zoologie, Masson & Cle., Paris, p. 97-148.
- DENCE, M., INNES, M. AND ROBERTSON, P., 1968. Recent Geological and Geophysical Studies of Canadian Craters. In French, B.M. and Short, N.M. (eds.) Shock Metamorphism of Natural Materials, Mono Book Corporation, Baltimore, p.339-361.
- DOE, B.R., 1970. Lead Isotopes, Berlin, Springer-Verlag, 137 p.
- DÖRR, H., MANGINI, A., SCHMITZ, W., WEBER, F. AND MÜNNICH, K.O., 1991. Stable lead and ^{210}Pb in German lake sediments and soils: a tracer for anthropogenic lead emission. In Vernet, J.-P. (ed.) Heavy Metals in the Environment, Elsevier, Amsterdam, p. 247-260.
- DOWLING, D.B., 1900. Report on the geology of the west shore of Lake Winnipeg; Geological Survey of Canada, Annual Report, v.11, Part F, 100 p.

DUJARDIN, F., 1840. Mémoire sur une classification des Infusoires en rapport avec leur organization. Comptes Rendus de l'Académie des Sciences de Paris, 11: 281-286.

DUJARDIN, F., 1841. Histoire Naturelle des Zoophytes. Infusoires: comprenant la physiologie et la classification de ces animaux, et la manière de les étudier à l'aide du microscope. Librairie Encyclopedique de Roret, Paris, text volume: 1-684, plates volume: 1-14, pls. 1-16, 16 bis, 17-22.

EHRENBERG, C.G., 1830. Organisation, systematik und geographisches Verhältnis der Infusionsthierchen. Druckerei der Königlichen Akademie der Wissenschaften, 108 p.

EHRENBERG, C.G., 1832. Über die Entwicklung und Lebensdauer der Infusionsthier, nebst fernerer Beiträgen zu einer Vergleichung ihrer organischen Systeme. Königliche Akademie der Wissenschaften zu Berlin Abhandlungen, 1831, Physikalische Abhandlungen, 154 p.

EHRENBERG, C.G., 1838. Die Infusionsthierchen als vollkommene Organismen. Ein Blick in das tiefere organische Leben der Natur. L. Voss, Leipzig, 547 p.

EHRENBERG, C.G., 1840. Das grössere Infusorienwerke. Königliche Preussischen Akademie der Wissenschaften zu Berlin Bericht, 1840, p. 198-219.

EHRENBERG, C.G., 1843a. Über die weitere Entwicklung der Verbreitung und des Einflusses des mikroskopischen Lebens in Afrika. Bericht über die zur Bekanntmachung geeigneten Verhandlungen der Königlichen Preussischen Akademie der Wissenschaften zu Berlin Abhandlungen, 1843, p. 133-143.

EHRENBERG, C.G., 1843b. Verbreitung und Einfluss des mikroskopischen Lebens in Süd- und Nord-Amerika. Königliche Akademie der Wissenschaften zu Berlin Abhandlungen, 1841, Physikalische Abhandlungen, p. 291-446.

EHRENBERG, C.G., 1848. Fortgesetzte Beobachtungen über jetzt herrschende atmosphärische mikroskopische Verhältnisse. Bericht über die zur Bekanntmachung geeigneten Verhandlungen der Königlichen Preussischen Akademie der Wissenschaften zu Berlin, p. 370-381.

EHRENBERG, C G., 1856. Über das mikroskopische Leben der centralen Landflächen Mittel-Afrika's. Monatsberichte der Königlichen Preussische Akademie der Wissenschaften zu Berlin, p. 323-338.

EHRENBERG, C.G., 1872. Nachtrag zur Übersicht der organischen Atmosphärilien. Königliche Akademie der Wissenschaften zu Berlin Abhandlungen, 1871, Physikalische Abhandlungen, p. 233-275.

EREL, Y., MORGAN, J.J., AND PATTERSON, C.C., 1991. Natural levels of lead and cadmium in a remote mountain stream. *Geochimica et Cosmochimica Acta*, 55: 707-719.

FARMER, J.G., EADES, L.J., MACKENZIE, A.B., KIRIKA, A. AND BAILEY-WATTS, T.E., 1996. Stable Lead Isotope Record of Lead Pollution in Loch Lomond Sediments since 1630 A.D. *Environmental Science and Technology*, 30: 3080-3083.

FAURE, G., 1986. *Principles of Isotope Geology*, Toronto, John Wiley and Sons Inc, 559 p.

- FENTON, M.M., MORAN, S.R. TELLER, J.T. AND CLAYTON, L., 1983. Quaternary Stratigraphy and History of the Southern Part of the Lake Agassiz Basin. In Teller, J.T. and Clayton, L. (eds.), Geological Association of Canada Special Paper 26, p. 49-74.
- FLANNAGAN, J.F., COBB, D.G. AND FLANNAGAN, P.M., 1994. A review of the research on the benthos of Lake Winnipeg. Canadian Manuscript Report of Fisheries and Aquatic Sciences No. 2261, 17 p.
- FLEGAL, A.R., NRIAGU, J.O., NIEMEYER, S., AND COALE, K.H., 1989. Isotopic tracers of lead contamination in the Great Lakes. *Nature*, 339: 455-458.
- FORBES, D.L. AND FROBEL, D., 1996. Shore-zone morphology and processes of Lake Winnipeg. In Todd, B.J., Lewis, C.F.M., Thorleifson, L.H., and Neilsen, E., (eds.), Lake Winnipeg Project: Cruise Report and Scientific Results, Geological Survey of Canada Open File 3113, p. 355-391.
- GARIÉPY, C., VERNER, D., AND DOIG, R., 1990. Dating Archean metamorphic minerals southeast of the Grenville front, western Quebec; using Pb isotopes. *Geology*, 18: 1078-1081.
- GAUTHIER-LIÈVRE, L., AND THOMAS, R., 1958. Les Genres Diffflugia, Pentagonia, Maghrebia, et Hoogenraadia (Rhizopodes testacés) en Afrique. *Archiv für Protistenkunde*, 103: 241-370.

- GOBEIL, C. AND SILVERBERG, N., 1989. Early diagenesis of lead in Laurentian Trough sediments. *Geochimica et Cosmochimica Acta*, 53: 1889-1895.
- GOBEIL, C., JOHNSON, W.K., MACDONALD, R.W., AND WONG, C.S., 1995. Sources and Burden of Lead in St Lawrence Estuary Sediments: Isotopic Evidence. *Environmental Science and Technology*, 23: 193-201.
- GRANEY, J.R., HALLIDAY, A.N., KEELER, G.J., NRIAGU, J.O., ROBBINS, J.A., AND NORTON, S.A., 1995. Isotopic record of lead pollution in lake sediments from the northeastern United States. *Geochimica et Cosmochimica Acta*, 59: 1715-1728.
- GRIFFIN, J.L., 1972. Movement, fine structure and fusion of pseudopods of an enclosed amoeba, Diffugiella sp. *Journal of Cell Science*, 10: 563-583.
- GROOM, H.D., 1985. Surficial geology and aggregate resources of the Fisher Branch area: Local Government District of Fisher and Rural Municipality of Bifrost. Manitoba Energy and Mines, Mineral Resources Division, Aggregate Report, 84-2, 33 p.
- HAMAN, D. AND KOHL, B., 1994. A thecamoebinid Assemblage from Lake Cocococha, Tambopata Reserve, Madre de Dios Province, Southeastern Peru. *Journal of Foraminiferal Research*, 24(4): 226-232.
- HANS, P. AND DOERING, J.C., 1995. An overview of the shoreline of the South Basin of Lake Winnipeg. Lake Winnipeg Workshop March 1995, Manitoba Energy and Mines Winnipeg; Manitoba.

- HART, S.R., AND TILTON, G.R., 1966. The isotope geochemistry of strontium and lead in Lake Superior sediments and water. In The earth beneath the continents, American Geophysical Union Geophysical Monograph no. 10, p. 127-137.
- HEAL, O.W., 1962. The abundance and micro-distribution of testate amoebae (Rhizopoda: Testacea) in Sphagnum. Oikos, 13: 35-47.
- HEMPEL, A., 1898. A list of the Protozoa and Rotifera found in the Illinois River and adjacent lakes at Havana, Ill. Bulletin of the Illinois State Laboratory of Natural History, 5: 301-321.
- HENDERSON, P.H., 1994. Surficial geology and drift composition of the Bissett-English Brook area, Rice Lake Greenstone Belt, southeastern Manitoba. Geological Survey of Canada, Open File 2910, 190 p.
- HENDERSON, P.J., 1996. Geochemistry of Lake Winnipeg sediments. In Todd, B.J., Lewis, C.F.M., Thorleifson, L.H., and Neilsen, E. (eds.), Lake Winnipeg Project: Cruise Report and Scientific Results, Geological Survey of Canada Open File 3113, p. 221-236.
- HERTWIG, R., AND LESSER, E., 1874. Über Rhizopoden und denselben nahestehende Organismen. Archiv für Mikroskopische Anatomie, 10.
- HOOGENRAAD, H. R. AND GROOT, A. A. DE., 1941. Observations on a special manner of feeding of a species of Diffugia (Diffugia rubescens Penard). Proceedings of the Nederlandsche Akademie Van Wetenschappen, 44: 217-228.

ICE THICKNESS CLIMATOLOGY, 1992. 1961-1990 normals, Ice climatology services,
Ministry of the Environment, Ottawa, p. 52-53.

JAWORSKI, J., 1987. Lead. In Hutchinson, T. C., and Meema, K. M. (eds.), Lead,
Mercury, Cadmium and Arsenic in the Environment (SCOPE: 31). , Chichester,
John Wiley and Sons, p. 3-16.

JOYON, L., AND CHARRET, R., 1962. Sur l'ultrastructure du Thécamoebien Hyalosphenia
papilio (Leidy). Comptes Rendus de l'Académie des Sciences de Paris, 255: 2661-
2663.

JUNG, W., 1942. Südchilenische Thekamöben (aus südchilenische Küstengebiet, Beiträg
10). Archiv für Protistenkunde, 95: 253-356.

KENT, S., 1880. A manual of the Infusoria, vol. 1. Bogue, London, 472 p.

KERR, H.A., 1984. Arcellaceans in Eastern Canada: selected biostratigraphic and
biological studies. Unpublished honours thesis, Dalhousie University, Halifax,
Nova Scotia, 49 p.

KING J.W. AND GIBSON, C., 1996. Paleomagnetic analysis of Lake Winnipeg core 122a.
In Todd, B.J., Lewis, C.F.M., Thorleifson, L.H., and Neilsen, E. (eds.), Lake
Winnipeg Project: Cruise Report and Scientific Results, Geological Survey of
Canada Open File 3113, p. 203-208.

KLASSEN, R.W., 1967. Surficial geology of the Waterhen-Grand Rapids area, Manitoba.
Geological Survey of Canada, Paper 66-36, 6 p.

KLASSEN, R.W., 1983. Lake Agassiz and the Late Glacial History of Northern Manitoba.

In Teller, J.T. and Clayton, L. (eds), Glacial Lake Agassiz. GAC Spec. Paper 26, p.75-96.

KLING, H.J. 1996. Fossil and modern phytoplankton from Lake Winnipeg. In Todd, B.J., Lewis, C.F.M., Thorleifson, L.H., and Neilsen, E., (eds.), Lake Winnipeg Project: Cruise Report and Scientific Results, Geological Survey of Canada Open File 3113, p. 283-310.

KLIZA, D.A., 1994. Distribution of Arcellacea in freshwater lakes of Pond Inlet and Bylot Island, Northwest Territories. Unpublished honours thesis, Carleton University, Ottawa, Ontario, 52 p.

KLIZA, D.A., 1997. An evaluation of the relative significance of natural versus anthropogenic sources of trace metals in a series of remote lakes in southeastern Ontario. Abstract, GAC-MAC Annual Meeting, Ottawa, p. A80.

KUSHNIR, D.W., 1971. Sediments in the South Basin of Lake Winnipeg. Unpublished M.Sc. thesis, University of Manitoba, Winnipeg, 92 p.

LAMARCK, J.B., 1816. Histoire naturelle des animaux sans vertèbres, vol. 2. Verdière, Paris, 568 p.

LAMINGER, H., 1972. Ein Beitrag zur Kenntnis der Hochgebirgs-Testaceen Österreichs. Archiv für Protistenkunde, Bd.114, p.101-151.

LANKESTER, E.R., 1885. Protozoa, p. 830-866. In The Encyclopedia Britannica.

LEIDY, J., 1874a. Notice of some Rhizopods. Academy of Natural Sciences of Philadelphia Proceedings, 155-157.

LEIDY, J., 1874b. Notice of some new fresh-water Rhizopods. Academy of Natural Sciences of Philadelphia Proceedings, 77-79.

LEIDY, J., 1876. Remarks on the Rhizopod Genus Nebela. Academy of Natural Sciences of Philadelphia Proceedings, 115-119.

LEIDY, J., 1879. Fresh-water Rhizopods of North America. United States Geological Survey of the Territories Report, 12, 324 p.

LEWIS, C.F., AND TODD, B.J., 1996. Lithology and seismostratigraphy of long cores, and a reconstruction of Lake Winnipeg water level history. In Todd, B.J., Lewis, C.F.M., Thorleifson, L.H., and Neilsen, E., (eds.), Lake Winnipeg Project: Cruise Report and Scientific Results, Geological Survey of Canada Open File 3113, p. 161-192.

LOCKHART, W. L., 1996. Recent sedimentation rates and toxic metal concentrations in Lake Winnipeg sediments. In Todd, B. J., Lewis, C. F. M., Thorleifson, L. H., and Neilsen, E., (eds.), Lake Winnipeg Project: Cruise Report and Scientific Results, Geological Survey of Canada Open File 3113, p. 237-240.

LOEBLICH, A.R. AND TAPPAN, H., 1964. Sarcodina, chiefly "Thecamoebians" and Foraminiferida. In Moore, R. C. (ed.), Treatise on Invertebrate Paleontology, Part

C, Protista 2. Geological Society of America and University of Kansas Press, Lawrence, p. C1-C510a.

LOUSIER, J. D., 1974. Response of soil Testacea to soil moisture fluctuations. *Soil Biology and Biochemistry*, 6: 235-239.

LOWE, C.W., 1924. The freshwater algae of Canada. *Transactions of the Royal Society of Canada*, 18: 19-48.

MANITOBA MINERALS DIVISION, 1987. Geological Highway Map of Manitoba, M.D.A Spec. Pub. No.1.

MAST, S.O. AND ROOT F. M., 1916. Observations on Amoebae feeding on Rotifers, Nematodes and Ciliates, and their bearing on the surface-tension theory. *Journal of Experimental Zoology*, 21: 33-49.

MATILE, G.L.D. AND GROOM, H.D., 1987. Late Wisconsinan stratigraphy and sand and gravel resources in the Rural Municipality of Lac du Bonnet and Local Government District of Alexander. Manitoba Energy and Mines, Mines Branch, Aggregate Report AR 85-2, 44 p.

MCANDREWS, J.H., 1988. Human disturbance of North American forests and grasslands: The pollen record. *In* Huntley, B., and Webb, T. I. (eds.), *Vegetation History*, Kluwer Academic Publishers, p. 673-697.

MCCARTHY, F.M.G., COLLINS, E.S., MCANDREWS, J.H., KERR, H.A., SCOTT, D.B. AND MEDIOLI, F.S., 1995. A comparison of postglacial arcellacean ("thecamoebian")

and pollen succession in Atlantic Canada, illustrating the potential of arcellaceans for paleoclimatic reconstruction. *Journal of Paleontology* 69(5): 980-993.

MCLEOD, K.D., 1995. Heritage resources of the Lake Winnipeg study area. Abstract, Proc. Lake Winnipeg Workshop, Winnipeg, March 1995.

MCMARTIN, I., 1996. Lake Agassiz beaches and reconstruction of lower lake levels in the Shield Margin area, northwest of Lake Winnipeg. In Todd, B.J., Lewis, C.F.M., Thorleifson, L.H., and Neilsen, E., (eds.), Lake Winnipeg Project: Cruise Report and Scientific Results, Geological Survey of Canada Open File 3113, p. 403-420.

MEDIOLI, F.S., 1997. Asexual Reproduction and Classification of Testate Rhizopods. Abstract, GAC-MAC Annual Meeting, Ottawa, p. A101.

MEDIOLI, F.S. AND SCOTT, D.B., 1983. Holocene Arcellacea (Thecamoebians) from Eastern Canada. *Cushman Foundation Special Publication*, 21, 63 p.

MEDIOLI, F.S. AND SCOTT, D.B., 1988. Lacustrine thecamoebians (mainly arcellaceans) as potential tools for palaeolimnological interpretations. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 62: 361-386.

MEDIOLI, F.S., SCOTT, D.B. AND ABBOTT, B.H., 1987. A case study of protozoan interclonal variability: taxonomic implications. *Journal of Foraminiferal Research*, 17: 28-47.

MEDIOLI, F.S., SCOTT, D.B., COLLINS, E.S. AND MCCARTHY, F.M.G., 1990. Fossil thecamoebians: present status and prospects for the future. In Hemleben, C.,

- Kaminski, M.A., Kuhnt, W. and Scott, D.B., (eds.), *Paleoecology, Biostratigraphy, Paleoceanography and Taxonomy of Agglutinated Foraminifera*: NATO Adv. Study Inst. Series C, Math. and Phy. Sci. 327, p. 813-840.
- Moss, B., 1988. *Ecology of Fresh Waters*, 2nd Ed. Blackwell Scientific Publications, Oxford, 417 pp.
- NAIR, K.N. AND MUKHERJEE, R.N., 1968. On some testacean rhizopods (Protozoa: Sarcodina) of the ground and tree mosses from Calcutta and its environs. *Proc. natn. Acad. Sci. India* 38B:185-193.
- NIELSEN, E., 1989. Quaternary stratigraphy and overburden geochemistry in the Phanerozoic terrane of southern Manitoba. Manitoba Energy and Mines, Geological Paper GP 87-1, 78 p.
- NIELSEN, E. AND L.H. THORLEIFSON, 1996. Quaternary geology of the Lake Winnipeg area. In Todd, B.J., Lewis, C.F.M., Thorleifson, L.H., and Neilsen, E., (eds.), *Lake Winnipeg Project: Cruise Report and Scientific Results*, Geological Survey of Canada Open File 3113, p. 141-157.
- NORFORD, B.S., HAIDL, F.M., BEZY, R.K., CECILE, M.P., MCCABE, H.R. AND PATERSON, D.F., 1994. Middle Ordovician to Lower Devonian strata of the Western Canada Sedimentary Basin. In Mossop, G.D. and Shetsen, I. (compilers), *Geological atlas of the Western Canada Sedimentary Basin*, Calgary, Canadian Society of Petroleum Geologists and Alberta Research Council, p.109-127.

- NRIAGU, J.O. AND PACYNA, J.M., 1988. Quantitative assessment of worldwide contamination of air water and soils by trace metals. *Nature*, 333: 134-139.
- OGDEN, C.G., 1983. Observations on the systematics of the genus Diffflugia in Britain (Rhizopoda, Protozoa). *Bulletin of the British Museum (Natural History)*, 44: 1-73.
- OGDEN, C.G. AND HEDLEY, R.H., 1980. An Atlas of Freshwater Testate Amoebae: *Bulletin of the British Museum (Natural History)*. London and Oxford University Press, Oxford, 222 p.
- PACYNA, J.M., MÜNCH, J. AND AXENFELD, F., 1991. European inventory of trace metal emissions to the atmosphere. *In* Vernet, J.-P., (ed.), *Heavy Metals in the Environment. Trace Metals in the Environment*, Amsterdam, Elsevier, p. 1-20.
- PATALAS, K. AND SALKI, A.G., 1992. Crustacean plankton in Lake Winnipeg: variation in space and time as a function of lake morphology, geology and climate. *Canadian Journal of Fisheries and Aquatic Sciences*, 49: 1035-1059.
- PATTERSON, R.T., BARKER, T. AND BURBIDGE, S.M., 1996. Arcellaceans (thecamoebians) as proxies of arsenic and mercury contamination in northeastern Ontario lakes. *Journal of Foraminiferal Research*, 26(2): 172-183.
- PATTERSON, R.T., MACKINNON, K.D., SCOTT, D.B. AND MEDIOLI, F.S., 1985. Arcellaceans ("Thecamoebians") in small lakes of New Brunswick and Nova Scotia: modern distribution and Holocene stratigraphic changes. *Journal of Foraminiferal Research*, 15: 114-137.

- PENARD, E., 1890. Études sur les Rhizopodes d'eau douce. Mémoires de la Société de Physique et d'Histoire Naturelle de Genève, 31, 230 p.
- PENARD, E., 1893. *Pelomyxa palustris* et quelques autres organismes inférieurs. Bibliothèque Universelle, Archives des Sciences Physiques et Naturelles, 29: 161-180.
- PENARD, E., 1899. Les Rhizopodes de faune profonde dans le lac Léman. Revue Suisse de Zoologie, 7: 1-142.
- PENARD, E., 1902. Faune rhizopodique du bassin du Léman. Henry Kundig, Genève, 714 p.
- PENARD, E., 1912. Notes sur quelques Sarcodiniés. Revue Suisse de Zoologie, 20: 1-29.
- PERTY, M., 1849. Mikroskopische Organismen der Alpen und der itlaienischen Schweiz. Naturforschende Gesellschaft in Bern Mittheilungen, 1849, p.153-176.
- PERTY, M., 1852. Zur Kenntnis kleinster Lebensformen nach Bau, Funktionen, Systematik, mit Spezialverzeichnis der in der Schweiz beobachteten. Jent and Reinert, Bern, 228 p.
- PLAYFAIR, G.J., 1918. Rhizopods of Sidney and Lismore. Proceedings of the Linnean Society New South Wales, 42: 633-675.

- RABAN, R., 1995. Lake Winnipeg: "A Manitoba Hydro Perspective". . Lake Winnipeg Workshop March 1995, Manitoba Energy and Mines Winnipeg; Manitoba.
- RENNBERG, I., PERSSON, M.W. AND EMTERYD, O., 1994. Pre-industrial atmospheric lead contamination detected in Swedish lake sediments. *Nature*, v.368, p.323-326.
- RHUMBLER, L., 1895. Beiträge zur Kenntnis der Rhizopoden. *Zeitschrift für wissenschaftliche Zoologie*, 61: 38-110.
- RITCHIE, J.C. AND YARRANTON, G.A., 1978. Patterns of change in the Late-Quaternary vegetation history of the Western Interior of Canada. *Canadian Journal of Botany*, 56: 2177-2183.
- RODRIGUES, C.G., 1996. Ostracode stratigraphy of Lake Winnipeg sediments. In Todd, B.J., Lewis, C.F.M., Thorleifson, L.H., and Neilsen, E., (eds.), *Lake Winnipeg Project: Cruise Report and Scientific Results*, Geological Survey of Canada Open File 3113, p. 261-266.
- RYBICKI, R.W., 1966. Limnological study of the North Basin of Lake Winnipeg; 1963 and 1964. Manitoba Department of Mines and Natural Resources, Fisheries Branch, 12 p.
- SCHLUMBERGER, P., 1845. Observations sur quelques nouvelles espèces d'Infusoires de la famille des Rhizopodes. *Annales Science Naturelles: Zoologie*, 3: 254-256.
- SCHMARDA, L.K., 1871. *Zoologie*, vol. 1. Braumüller, Wien, 372 p.

- SCHÖNBORN, W.S., 1984. Studies on remains of Testacea in cores of the Great Woryty Lake (NE-Poland). *Limnologica* (Berlin) 16: 185-190.
- SCHOUTEDEN, H., 1906. Les Rhizopodes testacés d'eau douce d'après la Monographie du Prof. A. Awerintzew. *Annales de Biologie Lacustre*, 1: 327-382.
- SCHULZE, F.E., 1877. Rhizopodenstudien VI. *Archiv für Mikroskopische Anatomie*, 13: 9-30.
- SCOTT, D.B. AND MEDIOLI, F.S., 1980. Quantitative studies of marsh foraminiferal distributions in Nova Scotia: implications for sea level studies. Cushman Foundation for Foraminiferal Research, Special Publication, 17, 58 p.
- SCOTT, D.B. AND MEDIOLI, F.S., 1983. Testate rhizopods in Lake Erie: modern distribution and stratigraphic implications. *Journal of Paleontology*, 57(4): 809-820.
- SIEBOLD, C.T.E.VON, 1845. Wirbellose Thiere: part 1. In Siebold, C.T.E. von and Stannuis, H. von (eds.), *Lehrbuch der Vergleichenden Anatomei*, p.1-679.
- SHIRAHATA, H., ELIAS, R.W. AND PATTERSON, C.C., 1980. Chronological variations in concentrations and isotopic compositions of anthropogenic atmospheric lead in sediments of a remote alpine pond. *Geochimica et Cosmochimica Acta*, 44: 149-162.

- STEIN, S.F.N.VON, 1859. Über die ihm aus eigener Untersuchung bekannt gewordenen Süswasser-Rhizopoden. Königliche Böhmishe Gesellschaft der Wissenschaften Abhandlungen, 10: 41-43.
- STERN, T.W., GOLDICH, S.S. AND NEWELL, M.F., 1966. Effects of weathering on the U-Pb ages of zircon from the Morton Gneiss, Minnesota. Earth and Planetary Science Letters, 1: 369-371.
- STUKAS, V.J. AND WONG, C.S., 1981. Stable lead isotopes as a tracer in coastal waters. Science, 211: 1424-1427.
- STUMP, A.B., 1935. Observations on the feeding of Diffflugia, Pontigulasia and Lesquereusia. Marine Biological Laboratory, Woods Hole, Biological Bulletin, 69: 136-142.
- STURGES, W.T. AND BARRIE, L.A., 1987. Lead 206/207 isotope ratios in the atmosphere of North America as tracers of US and Canadian emissions. Nature, 329: 144-146.
- STURGES, W.T. AND BARRIE, L.A., 1989. The use of stable lead 206/207 isotope ratios and elemental composition to discriminate the origins of lead in aerosols at a rural site in Eastern Canada. Atmospheric Environment, 23: 1645-1657.
- TARÁNEK, K.J., 1881. Beiträge zur Kenntniss der Süswasser-Rhizopoden Böhmens. Königliche Böhmishe Gesellschaft der Wissenschaften, Sitzungsber., 1881, p.220-235.

- TARNOCAE, C., 1970. Glacial history, surface deposits, soils and vegetation of Wekusko and portions of Cross Lake, Norway House and Grand Rapids map area, Manitoba. 14th Annual Manitoba Soil Science Meeting, p.22-25.
- TELLER, J.T. AND J.P. BLUEMLE, 1983. Geological setting of the Lake Agassiz region. In Teller, J.T. and Clayton, L. (eds.), Geological Association of Canada Special Paper 26, p. 7-20.
- TELLER, J.T. AND L.H. THORLEIFSON, 1983. The Lake Agassiz-Lake Superior Connection. In Teller, J.T. and Clayton, L. (eds.), Geological Association of Canada Special Paper 26, p. 261-290.
- TESSIER, A., CAMPBELL, P.G.C., AND BISSON, M., 1979. Sequential extraction procedure for the speciation of particulate trace metals. *Analytical Chemistry*, 51: 844-850.
- THIBAudeau, S.A., MEDIOLI, F.S. AND SCOTT, D.B., 1987. Carboniferous marginal-marine Rhizopods: a morphological comparison with recent correspondents. Abstract, GSA Annual Meeting, Phoenix 866.
- TODD, B.J., 1996. Cruise report of the 1994 Lake Winnipeg Project: Namao 94-900. In Todd, B.J., Lewis, C.F.M., Thorleifson, L.H., and Neilsen, E., (eds.), Lake Winnipeg Project: Cruise Report and Scientific Results, Geological Survey of Canada Open File 3113, p. 7-76.
- TODD, B.J. AND C.F.M. LEWIS, 1996. Seismostratigraphy of Lake Winnipeg sediments. In Todd, B.J., Lewis, C.F.M., Thorleifson, L.H., and Neilsen, E., (eds.), Lake

Winnipeg Project: Cruise Report and Scientific Results, Geological Survey of Canada Open File 3113, p. 79-117.

TORIGAI, K., 1996. Distribution of recent thecamoebians in Lake Winnipeg. Unpublished honours thesis, Carleton University, Ottawa, Ontario, 57 p.

TYRRELL, J.B. AND DOWLING, D.B., 1900. Report on the east shore of Lake Winnipeg and adjacent parts of Manitoba and Keewatin. Geological Survey of Canada, Annual Report, v. 11, Part G, 98 p.

UPHAM, W., 1890. Report on the exploration of the Glacial Lake Agassiz in Manitoba. Geological Survey of Canada Annual Report for 1888-1889, v. 5, Section E, 156 p.

VALKANOV, A., 1966. Über die Fortpflanzung der Testaceen (Rhizopoda-Testacea). [Bolgarska Akademiya na naukite, Izvestiya na Zoologischeskiya Institut s Muzei] Bulgarian Academy of Science. Bulletin of the Institute and the Museum of Zoology (Sofia), 22: 5-49.

VANCE, R.E., 1996. Paleobotany of Lake Winnipeg sediments. In Todd, B.J., Lewis, C.F.M., Thorleifson, L.H., and Neilsen, E., (eds.), Lake Winnipeg Project: Cruise Report and Scientific Results, Geological Survey of Canada Open File 3113, p. 311.

WAILES, G.H., 1919. Supplement to Rhizopods. In Cash, J., Waiiles, G.H. and Hopkinson, J. (eds.), The British freshwater Rhizopoda and Heliozoa, Ray Society, London, p. 1-71, pls. 58-63.

- WALLICH, G.C., 1864. On the extent, and some of the principal causes, of structural variation among the difflugian rhizopods. *Annals and Magazine of Natural History*, 13: 215-245.
- WARD, G., 1926. Seasonal variation in the composition of the Red River. Unpublished M.Sc. thesis, University of Manitoba, Winnipeg, 24 p.
- WEBER, W., 1990. The Churchill-Superior Boundary zone, southeast margin of the Trans-Hudson Orogen: a review. In Lewry, J.F. and Stauffer, M.R. (eds.), *The Early Proterozoic Trans-Hudson Orogen of North America*, Geological Association of Canada Special Paper 37, p.41-57.
- WEBER, W., 1996. Precambrian geology of the Lake Winnipeg area. In Todd, B.J., Lewis, C.F.M., Thorleifson, L.H., and Neilsen, E., (eds.), *Lake Winnipeg Project: Cruise Report and Scientific Results*, Geological Survey of Canada Open File 3113, p. 119-125.
- WEST, G.S., 1901. On some British freshwater Rhizopods and Heliozoa. *Linnean Society of London Journal, Zoology*, v.28, no.183, p.308-342.
- WILLIAMS, H.R., STOTT, G.M., THURSTON, P.C., SUTCLIFFE, R.H., BENNETT, G., EASTON, R.M. AND ARMSTRONG, D.K., 1992. Tectonic evolution of Ontario: summary and synthesis. In Thurston, P.C., Williams, H.R., Sutcliffe, R.H. and Stott, G.M. (eds.), *Geology of Ontario, Special Volume 4, Part 2*, p.1255-1332,

Appendix 1-1: Gravity/piston and box core data.

Site Number	Latitude	Longitude	Water depth	Sample Type	Recovery (cm)
101	53 12.02	99 06.99	12.2	box core	47
102	53 28.10	98 20.20	15.9	box core	52
103	53 27.29	98 21.95	15.9	piston	816
104a	53 35.05	98 05.11	16.1	gravity	375
104b	53 35.04	98 05.07	15.8	piston	670
105	53 35.64	98 03.80	15.9	piston	612
106	53 34.70	98 05.83	17.1	piston	800
107	52 55.85	97 47.31	17.1	piston	715
108	52 50.41	98 02.29	17.1	box core	47
110a	52 00.15	97 01.45	11.3	gravity	237
110b	52 00.15	97 01.45	11.3	box core	47
113a	51 24.09	96 37.53	9.8	gravity	216
113b	51 24.08	96 37.52	9.8	box core	50
114	50 58.74	96 39.39	10.7	box core	58
115	50 56.76	96 40.90	10.7	gravity	283
116	50 39.86	96 47.98	10.1	box core	50
117	50 50.00	96 49.20	10.4	box core	0
118	50 45.32	96 29.15	7.9	box core	38
119	50 48.19	96 31.81	9.8	gravity	329
120	50 48.91	96 32.70	10.1	piston	359
121	50 50.00	96 49.20	10.4	gravity	558
122a	50 39.39	96 48.28	9.8	gravity	488
123	50 32.49	96 49.99	9.1	box core	0

Appendix 4-1: Thecamoebian Faunal List

Species recognized in Lake Winnipeg sediments are listed below with author and date citations. Morphological variations of some species, termed strains, are designated by non-latinized names in quotation marks. The original designation is given in square brackets if it differs from the present designation. Selected taxa are illustrated in Figure 4-9.

Arcella vulgaris Ehrenberg, 1830

Centropyxis aculeata (Ehrenberg, 1832) [Arcella]

Strain: Centropyxis aculeata "aculeata"

Strain: Centropyxis aculeata "discoides"

Strain: Centropyxis aculeata "ecornis"

Centropyxis constricta (Ehrenberg, 1843b) [Arcella]

Diffugia protaeiformis Lamarck, 1816

Strain: Diffugia protaeiformis "protaeiformis"

Strain: Diffugia protaeiformis "elegans"

Strain: Diffugia protaeiformis "inflata"

Diffugia ampullula Playfair, 1918

Diffugia fragosa Hempel, 1898

Strain: Diffugia fragosa "fragosa"

Strain: Diffugia ?fragosa "strain a"

Diffugia globulus (Ehrenberg, 1848) [Arcella]

Diffugia manicata Penard, 1902

Diffugia oblonga Ehrenberg, 1832

Strain: Diffugia oblonga "oblonga"

Strain: Diffugia oblonga "lacustris"

Strain: Diffugia oblonga "lanceolata"

Strain: Diffflugia oblonga "linearis"

Diffflugia urceolata Carter, 1864

Strain: Diffflugia urceolata "urceolata"

Strain: Diffflugia urceolata "amphora"

Strain: Diffflugia urceolata "lebes"

Diffflugia urens Patterson, MacKinnon, Scott and Medioli 1985

Diffflugia viscidula Penard, 1902

Lagenodiffflugia vas (Leidy, 1874a) [Diffflugia]

Pontigulasia compressa (Carter, 1864) [Diffflugia]

Awerintzewia cyclostoma (Penard, 1902) [Heleopera]

Cucurbitella corona (Wallich, 1864) [Diffflugia]

Cucurbitella tricuspidis (Carter, 1856) [Diffflugia]

Heleopera sphagni (Leidy, 1874a) [Diffflugia]

Lesquereusia spiralis (Ehrenberg, 1840) [Diffflugia]

Oopyxis sp.

Trigonopyxis arcula (Leidy, 1879) [Diffflugia]

Cyclopyxis arcelloides (Penard, 1902) [Centropyxis]

Phryganella acropodia (Hertwig and Lesser, 1874) [Diffflugia]

Euglypha alveolata Dujardin, 1841

Appendix 5-1: Decay Series of Uranium and Thorium (after Faure, 1986; Doe 1970).

Appendix 5-2:

Correction factors determined by repeated analysis of the NBS 981 standard to compensate for machine fractionation of measured isotopic ratios.

$$^{206}\text{Pb}/^{204}\text{Pb}_{\text{corr}} = ^{206}\text{Pb}/^{204}\text{Pb}_{\text{meas}} + (^{206}\text{Pb}/^{204}\text{Pb}_{\text{meas}} \times 0.0027827)$$

$$^{207}\text{Pb}/^{204}\text{Pb}_{\text{corr}} = ^{207}\text{Pb}/^{204}\text{Pb}_{\text{meas}} + (^{207}\text{Pb}/^{204}\text{Pb}_{\text{meas}} \times 0.004148)$$

$$^{208}\text{Pb}/^{204}\text{Pb}_{\text{corr}} = ^{208}\text{Pb}/^{204}\text{Pb}_{\text{meas}} + (^{208}\text{Pb}/^{204}\text{Pb}_{\text{meas}} \times 0.0055887)$$