MICROPALEONTOLOGICAL APPLICATIONS IN ENVIRONMENTAL STUDIES: ARCELLACEANS AS PROXIES OF CHEMICAL POLLUTION IN LAKES, AND FORAMINIFERA AS PROXIES FOR HOLOCENE PALEOSEISMIC AND PALEOCLIMATIC RECORD IN OCEANS

By

Arun Kumar, B. Sc., M. Sc.

A thesis submitted to the Faculty of Graduate Studies and Research

in partial fulfillment of

the requirements for the degree of

Doctor of Philosophy

Ottawa-Carleton Geoscience Centre

and

Department of Earth Sciences
Carleton University

Ottawa, Ontario Canada
June, 1999

The undersigned hereby recommend to

the Faculty of Graduate Studies and Research

acceptance of the thesis,

MICROPALEONTOLOGICAL APPLICATIONS IN ENVIRONMENTAL STUDIES: ARCELLACEANS AS PROXIES OF CHEMICAL POLLUTION IN LAKES, AND FORAMINIFERA AS PROXIES FOR HOLOCENE PALEOSEISMIC AND PALEOCLIMATIC RECORD IN OCEANS

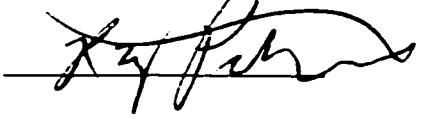
submitted by

ARUN KUMAR, B. Sc., M. Sc.

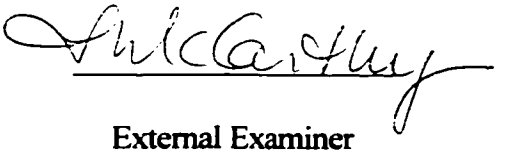
in partial fulfilment of the requirements

for the degree of Doctor of Philosophy

Chair, Department of Earth Sciences



Thesis Supervisor



External Examiner

Carleton University

June, 1999

TABLE OF CONTENTS

To my parents

Mrs Shanti Devi Srivastava (1930-1962)

Mr. Krishna Kant Srivastava (1923-1992)

GENERAL ABSTRACT

Arcellaceans (Thecamoebians) were studied from sediment-water interface samples from James Lake in northeastern Ontario to test them as possible proxies for chemical pollution. The southwestern part of the lake has been impacted by dumping of waste rock from a pyrite mine which existed close to its shore. High levels of Fe, Al and SO_4, and low pH (2.0-5.5) were recorded in this part of the lake. Lake configuration and current direction from north to south result in the contaminated area being restricted to the southern part of the lake, and almost neutral pH and low metal levels were recorded elsewhere. Arcellacean faunas indicate that *Arcella vulgaris* is able to thrive in highly acidic environments (pH range between 2.0 - 5.5). The absence of arcellaceans indicative of contaminated substrates in higher pH lakes, such as Centropyxids and *Difflugia protaeiformis* strains, suggests that pH is the dominant control on the distribution of *Arcella vulgaris* dominated assemblage. Arcellacean analysis from a shallow core at the contaminated site indicates that contamination and acidification (pH values <5.5) in southwestern part of James Lake have existed for at least 1300 years, thereby predating mining activity. Six assemblages representative of distinct Arcellacean habitats were recognized using Q-mode cluster analysis. R-mode cluster analysis of these distributional data indicates that Arcellacean strains from within the same species are useful for discriminating environments.

Benthic foraminifera were studied from the core sediments of anoxic Saanich Inlet to use them as possible proxies for paleoclimatic and paleoceanographic changes during the past ~15 k yr BP. Two long ODP (Leg 169S) cores in holes 1033B (105 m thick) and 1034B (118 m thick) from Saanich Inlet were studied. Sediments of this fjörd on the southern part of Vancouver Island consist of varved clays interbedded with slightly coarser massive layers. The fauna is impoverished; only 25 species of benthic foraminifera were identified and few (average of 25-30) specimens occurred in most of the samples. The foraminifers in these deep water sediments are predominantly shallow water, benthic, calcareous forms. Massive layers contained statistically higher numbers and greater diversity of benthic foraminifera than varves. A high proportion (>50%) of the fauna was found to be broken/damaged, and the presence of arcellaceans along with high proportion of broken/damaged foraminiferal specimens in massive layers supports the hypothesis that they were transported from shallow well oxygenated parts of the inlet and deposited on the anoxic bottom of Saanich Inlet during seismically-induced subaqueous debris flows. Intact benthic foraminifera within the varves are autochthonous, capable of withstanding dysoxic/anoxic conditions, and broken specimens are usually of allochthonous origin, being transported to the deeper anoxic parts of the inlet during spring freshet along with mineral-rich silt. Based on these results the maximum

periodicity of slumps generated by small to medium sized earthquakes (minimum M >4.5) averages to be every 170 years at narrower and steeper Site 1033, and larger earthquakes are estimated to occur every 280 years at wider and less steep Site1034. The higher recurrence rate at Site 1033 is because of relatively steep walls in the narrow part of the inlet which are less stable than the other areas of Saanich Inlet.

Q-mode cluster analysis of the foraminiferal data was used to define the five distinct biofacies. They are: *Stainforthia feyling-Buccella frigida* biofacies, *Buccella frigida-Lobatula fletcheri* biofacies, *Nonionella stella-Stainforthia feylingi* biofacies, *Islandiella helenae-Spirosigmoilina tenuis* biofacies, and *Siphonaperta stalkeri-Cribroelphidium excavatum* biofacies. The distribution of these biofacies is controlled primarily by the process of late Pleistocene deglaciation and associated sea-level changes and the development of anoxic conditions during the early Holocene in Saanich Inlet.

ACKNOWLEDGMENTS

Part A of this thesis on the study of arcellaceans was funded by NSERC Research Grant OGP 0041665 to RTP and a Cushman Foundation for Foraminiferal Research grant to me. I gratefully acknowledge the assistance of students in the Department of Earth Sciences Environmental Geology Field Camp (67.285) for their help in the field.
Part B of this thesis on the study of foraminifera was funded by NSERC research grant and NSERC collaborative special grant to RTP.

I am grateful to Dr. R. T. Patterson for offering me to work on these projects, and for financial help and encouragement during the course of this study. His editorial comments and suggestions were very useful. I am also grateful to Dr. F. E. Michel of the Department of Earth Sciences, Carleton University, for helping me in collecting sediment samples, pore water samples and providing ^{14}C dates. Dr. Jim Cheetham of the Department of Biological Sciences, Carleton University, Dr. Marie Anne Geurts of the Department of Geography, Ottawa University, and Dr. Francine McCarthy of the Department of Earth Sciences, Brock University for finding time to sit for my thesis defense.

I am also thankful to Dr. Brian Bornhold and Dr. Melissa McQuoid of the University of Victoria and Mr. Kim Conway of Pacific Geoscience Centre, Geological Survey of Canada, Sidney, B. C. for providing me information and core samples from Saanich Inlet.

I am thankful to my colleagues and friends, Andrew Dalby, Bob Boudreau and Patrick Lyons for helping me in computer work. Several times during the preparation of this thesis I was held up due to computer problems and needed help, my daughter Anita always solved my problems with a smile. I am very much grateful to her. Last but not least, I am grateful to my wife Sushma, son Anshuman and once again to my daughter Anita for constant emotional and moral support and they demonstrated a great deal of maturity and understanding during these "not so easy" years of my life.

ORIGINAL CONTRIBUTION

Tourism is one of the main economic activities of Temagami - Cobalt region of northeastern Ontario. The lakes of the region are a prime attraction for people who either live there or visit. Silver and pyrite mines have dumped their tailings and waste rocks in the lakes in the past causing chemical pollution. There has been a growing concern in the region about this problem. I studied arcellaceans from James Lake as this lake is chemically polluted only in the southwestern portion, whereas rest of the lake is normal to near normal. This project was initiated with help of Drs. R. T. Patterson and F. A. Michel. Students of the Cobalt Field Camp helped me in collection of samples in the summer of 1996 and 1997. All the work of processing the sediments, counting, analyzing and studying was done by me. The chemical analysis of the selected samples were done by ARECO Canada in Nepean, Ontario.

Arcellaceans are known as good bio-environmental indicators. Patterson et al. (1996) demonstrated a relationship between Arcellacean distribution and mercury and arsenic contamination in lakes polluted by silver mine tailings. Asioli et al. (1996) and Reinhardt et al. (1998) further showed that Arcellacean species and their infrasubspecific ecophenotypic populations termed as "strains" are also useful indicators of chemical pollution in lakes caused by industrial and mining activities. My James Lake study demonstrates the use of both Arcellacean species and "strains" as proxies for varying degrees of lake bottom acidity, chemical pollution and remediation. I have also shown that

arcellaceans can be successfully used for long term environmental stresses in lakes caused by natural processes.

Two Sites, 1033 and 1034, were cored in Saanich Inlet, in southern Vancouver Island, B.C. in 1996 by the Ocean Drilling Program (ODP). This inlet is an anoxic basin and has a complete record of late Pleistocene-Holocene sediments. I studied benthic foraminifera from these core samples. The core samples were processed at Pacific Geoscience Centre, Sydney, B.C. and sand fractions along with sedimentological data were sent to me for foraminiferal study by Mr. Kim Conway. My contribution to the ODP project was to demonstrate the use of benthic foraminifera as proxy for paleoclimatic and paleoceanographic changes in the southern part of Vancouver Island over the past ~15,000 years.

Paleoseismicity studies mainly depend on the stratigraphic, sedimentological, sedimentary structures and microfossil (pollen and diatom) evidences. Saanich Inlet sediments provided a unique opportunity to study benthic foraminifera from seasonally deposited varved sediments and associated massive sediments generated by subaqueous sediment flows. By demonstrating that massive sediments were generated by seismic activity, I was able to calculate the frequency and magnitude of earthquakes in southern Vancouver Island for the past 7,645 years. I have shown that massive sediments have higher numerical abundance and higher species diversity of benthic foraminifera than varves. Massive sediments contain shallow water benthic foraminifera, a large proportion

of which are either broken or damaged indicating their allogenic origin and transport from shallower regions of the inlet into the deeper parts.

LIST OF FIGURES

LIST OF TABLES

LIST OF PHOTOPLATES

LIST OF APPENDICES

TABLE OF CONTENTS

INTRODUCTION

METHOD OF PRESENTATION

This dissertation is presented in the form of five scientific journal articles. Since this research belongs to the realm of "Environmental Micropaleontology", the role of micropaleontological research in dealing with environmental problems is discussed in a general introduction. Papers 1, 2 and 3 deal with Arcellaceans (Thecamoebians) as proxies for detecting and monitoring chemical pollution due to mining activities in the lakes. These three papers demonstrate the use of micropaleontology in addressing the anthropogenic environmental problems. Paper 4 shows how benthic foraminiferal analysis in association with sedimentological data can be successfully used to detect the frequency and magnitude of paleoseismic records of the past over seven thousand years. Finally, paper 5 deals with foraminiferal use as proxies for paleoclimatic and paleoceanographic changes in Saanich Inlet over the past ~15 k yr.

ENVIRONMENTAL MICROPALEONTOLOGY - using microfossils as environmental proxies

Right from the origin of planet Earth, its environment has constantly been changing as a result of complex interaction among the physical, chemical and biological parameters that act upon the Earth's surface and its interior. Global warming, sea-level changes and chemical pollution of atmosphere and hydrosphere are important environmental problems that affect the entire global human population. These are actually naturally occurring environmental phenomena, but there is a growing concern that

anthropogenic activities such as burning of fossil fuels, deforestation and unchecked and ongoing industrialization, all in the name of "social and economic growth" is likely to be enhancing such environmental problems. It is necessary to study and understand such problems in terms of their genesis, processes and possible consequences to the living world, particularly to human beings. Thus there is a need for proxy indicators for a variety of environmental problems.

A wide variety of biological proxies have been used to detect and monitor various types of environmental problems in aquatic environments (Loeb and Spacie, 1994). To detect and monitor the mining related chemical pollution in various aquatic environments in Canada, Canada Centre for Mineral and Energy Technology (CANMET) launched "Aquatic Effects Technology Evaluation (AETE) Program". The AETE reports contain valuable information on using biological proxies for water and sediment monitoring, toxicity testing and field monitoring studies (CANMET reports, 1997). Scott et al. (ms.) have discussed in detail the utility of benthic foraminifers and thecamoebians in detecting and monitoring a wide variety of aquatic (both marine and terrestrial) environmental stresses caused naturally and anthropogenically.

The advantages of using benthic foraminifera and thecamoebians as environmental proxies are (1) that they have high species diversity and widespread geographic distribution, (2) one requires only a limited size of sample to be statistically significant, and (3) they both leave a fossil record which allows reconstruction of the history of a stressed site in the absence of original baseline data, thus enabling the historical reconstruction (Scott et al. ms.). Both these groups of related organisms are good

ecosystem indicators because they occur abundantly as diverse populations and are durable as fossils. They are easy to collect and process and cost effective to study. Their combination allows us to characterize and monitor all modern and ancient aquatic environments (Scott et al. ms.)

The literature about the use of microfossils as environmental proxies is limited. During the past decade this subject has constantly grown due to environmental concern and urgent need to study environmental problems. Foraminifers and thecamoebians are very susceptible to change under environmental stress. Depending on the environmental stress, they undergo morphological modifications (Boltovskoy et al. 1991; Reinhardt et al. 1998; Yanko et al. 1998). This dissertation demonstrates their utility as proxies for natural and anthropogenic environmental change. It is now well documented that arcellaceans are sensitive to environmental fluctuations, and are good bio-environmental indicators. Patterson et al. (1996) and Reinhardt et al. (1998) demonstrated a link between arcellacean distribution and mercury and arsenic contamination in small lakes polluted by mine tailings in northeastern Ontario, and have demonstrated that both arcellacean species and their infrasubspecific, ecophenotypic populations termed "strains" are also useful in identifying various chemically polluted and remediated environments in the lakes. Asioli et al. (1996) found several arcellacean "morphs" (= "strains") to be useful indicators of low oxygen environments rich in organics and sulfites, and in lakes of northern Italy.

THE PROTISTS

The protists are motile, unicellular organisms with varied body plans. Both Arcellaceans (Thecamoebians) and Foraminifers are "animal" protists and commonly referred to as testate rhizopods. They both belong to the Kingdom Protista; Phylum Sarcodina; and Class Rhizopoda (Loeblich and Tappan, 1964 a; Brasier, 1980). Foraminifers belong to the Order Foraminiferida Eichwald 1830 and Arcellaceans belong to the Order Arcellinida, Kent 1880. The term "Thecamoebians", and "Testacea" are also used by micropaleontologists for species belonging to the Order Arcellacea, Kent 1988, the Order Gromida, Claparede and Lachman 1859 and few species of the Suborder Allogromiina, Loeblich and Tappan 1961 of the Order Foraminiferida, Eichwald 1830 (Loeblich and Tappan, 1964 a). A more recent classification for foraminifers is provided by Culver (1993) as follows:

Kingdom	Protista
Subkingdom	Protozoa
Phylum	Sarcomastigophora Honigberg and Balamuth, 1963
Subphylum	Sarcodina Schmarda, 1871
Superclass	Rhizopoda von Siebold, 1845
Class	Granuloreticulosa De Saedeleer, 1934

A - Arcellaceans (Thecamoebians)

"Thecamoebians" are an artificial polyphyletic group of Protozoans. They are also commonly referred to as arcellaceans, agglutinated rhizopods, or testate amoebae, and are

characterized by the presence of pseudopods of variable nature, an amoeboid sarcodine cell and a very simple sac-like or cap-like test. The test of thecamoebians can be secreted by the organisms themselves (autogenous tests), either proteinaceous, siliceous, or rarely calcareous. Many of them build their tests by agglutinating foreign particles (xenosomes) in autogenous cement (xenogenous tests). This type is common in the fossil record during late Quaternary or possibly in Carboniferous. The nature of xenosomes is entirely controlled by the composition of the substrate, and may consist of silt grains and/or diatom frustules (Medioli et al. 1990). Arcellaceans, the most commonly fossilized type of thecamoebians, are a benthic microfaunal group that occur worldwide in bodies of fresh to brackish water. They have a long, albeit scanty, fossil record which goes back to Carboniferous Period (Vasicek and Ruzicka, 1957; Thibaudeau and Medioli,1986; and Thibaudeau et al., 1987). Their fossil record is mainly from lake or peat deposits. Their small size (60-300 μm) and high abundances mean that statistically significant populations are present even in small samples. They are very useful for paleolimnological studies, because they are among the few benthic organisms that are preserved in freshwater sedimentary environments, mollusks and ostracodes, for instance, are subject to dissolution in the low pH conditions typical of lake environments (Medioli and Scott, 1988).

Thecamoebians reproduce asexually. The fact that they are uniparental organisms has led to serious taxonomic problems with the group (Medioli and Scott, 1983; Medioli et al. 1987). Thecamoebians are usually grouped into specific units on the basis of test morphology. Environmentally controlled thecamoebian morphotypes (strains) occur

abundantly in nature, and most of the work so far has focused on creating new species of local interest. The nomenclatural confusion has led to two extreme taxonomic approaches: (a) that all thecamoebians belong to the same species (Wallich, 1864) or, (b) that every morphotype that occurs more than a few times represents a genuine species (Ogden and Hedley, 1980). This second approach to arcellacean taxonomy progressed to such a degree that Medioli et al. (1990) stated that the vast majority of species used in the literature are oversplit and thus useless for paleoecological purposes. Medioli and Scott (1983) proposed that arcellacean species be considered as a widely variable group that collectively, for any given wild population, accommodate 75% or more of the entire population. Although this concept is subjective, this approach does make allowance for a substantial amount of observed morphological instability. Asioli et al. (1996) and Reinhardt et al. (1998) have defined several environmentally useful "strains" within species. This infrasubspecific level classification is quite useful in delineating large populations of arcellaceans into ecophenotypes without describing more new species.

Thecamoebians are continental benthic organisms and occur in most areas where sufficient moisture is found (e.g. soils, mires, peat bogs, ponds and lakes etc.; Medioli et al., 1990). Most lacustrine thecamoebian species prefer oligotrophic and acidic waters, and are found in reduced numbers in eutrophic lakes. Ecological factors controlling the distribution pattern of arcellaceans include dissolved oxygen content, dystrophy-grade of the lake (C/N ratio in sediment which depends upon the existence of humic compounds), the grain size of sediment, and the existence of *Sphagnum* carpet around the lake (Tolonen, 1986).

Paleoecological studies using arcellaceans to address paleohydrological changes in peat lands and lakes, lake level changes and paleoclimatological changes have been done (Haman, 1982; Scott and Medioli, 1983; Patterson et al. 1985; Tolonen, 1986; Honig and Scott, 1987; Medioli and Scott, 1988, Collins et al. 1990, and McCarthy et al.1995). Thecamoebians are also known from brackish water marginal marine environments (Todd and Bronnimann,1957 and Hayward et al. 1996).

Changes in thecamoebian faunas provide strong evidence of environmental changes in the modern peat lands, and have been successfully used in similar studies of Quaternary peats (Warner, 1990; Warner and Charman, 1994; and Warner and Bunting, 1996).

B - Foraminifers

Foraminifers are very significant group of fossils, studied by a large number of micropaleontologists for a wide variety of geological, biological and environmental problems. General background information about this group of microfossils is provided by Tappan and Loeblich (1969), Tappan (1971), Haq and Boersma (1978) Brasier (1980) and Culver (1993). The following introductory remarks on foraminifers are mostly from Culver (1993).

Foraminifers include both planktic and benthic species. They are quite ubiquitous and inhabit brackish/marine environments ranging from the intertidal zone to deep ocean floor and from the polar regions to the tropics. They have a variety of test composition and very high morphological diversity. They occur throughout the Phanerozoic, and major

taxonomic diversification occurred in the Devonian and in the Triassic to early Jurassic which resulted in evolutionary innovations in test construction and morphology (Culver, 1993).

Foraminiferal skeletons or tests are built of chambers, which are cavities containing the cytoplasm with a surrounding firm wall. Adjacent chambers are separated by septa but a connection is maintained by a hole, or foramen, for which the Order Foraminiferida is named. The opening on the last chamber, through which pseudopodia extrude, is termed the aperture (Culver, 1993). Tests may be single or multichambered. Multichambered forms exhibit sutures, the external line of junction between adjacent chambers that may be arranged in a variety of ways. When later chambers envelope earlier ones the test is called involute, and when earlier chambers are visible the test is termed evolute. The test may coil in a single plane (planispiral) or in a spire (trochospiral), and each coil of the test is called a whorl (Culver, 1993).

Three basic wall compositions have been recognized in the foraminifera: organic (membranous or tectinous), agglutinated or arenaceous (foreign particles held together by various cements), and secreted calcium carbonate or silica. In agglutinated and secreted tests an organic membrane forms the foundation for the overlying skeletal material (Culver, 1993). The agglutinated foraminifera are the most primitive and can live where no carbonate is available; for example, in areas where lower salinity or colder water make the precipitation of carbonate difficult or impossible. Generally, as salinity and temperature rises, agglutinated species are replaced by forms secreting a $CaCO_3$ test (Greiner, 1970), unless the pH is lowered by either low oxygen or high organic carbon (or both in

combination). These conditions are often present in polluted environments (Schafer, 1973; Schafer et al. 1975; Vilks et al. 1975; Scott et al. ms.).

The tests of many species of foraminifera are dimorphic, which involves differences in size or morphology, and it is the result of alternation of sexual and asexual generations. Foraminifera are different from most other Protozoans in having an asexually produced uninucleate haploid generation (gamont) alternating with sexually produced multinucleate diploid generation (agamont or schizont). In some taxa simple fission or budding may also occur. Asexually formed specimens generally have more protoplasm initially and form a larger proloculus, hence they are termed megalospheric. Specimens developing from gametes have less initial protoplasm and form a smaller proloculus; hence they are termed microspheric (Culver, 1993).

Foraminiferal classification and evolution is a subject of constant change due to the availability of new morphological, biological and paleontological information (Loeblich and Tappan, 1964 b,1974,1982). The most comprehensive classification of foraminifera to date was proposed by Loeblich and Tappan (1988).

Benthic foraminifera have been especially useful in paleoenvironmental, paleoceanographic and paleoclimatic studies. Trends in species diversity, planktic:benthic ratios, shell type ratios, and foraminiferal morphology are useful for paleoenvironmental assessment. The inference of paleodepth and any other paleoecological parameter based on the known depth distribution of modern foraminiferal taxa is termed the taxonomic approach. Generally species diversity increases offshore from the shoreline to the continental slope where it may stay or decline, and planktic:benthic ratios also exhibit a

similar trend. Foraminifera have been extensively used in oil industry for biostratigraphic zonation and correlation (Culver, 1993).

The comparatively high species diversity of benthic foraminifera and thecamoebians renders local assemblages responsive to a broad range of environmental change (Scott et al. ms). Foraminifera are often the last group of organisms to disappear completely at sites that are being heavily impacted by industrial contamination. They also occur in transition zones that do not appear to be utilized efficiently by other kinds of marine organisms (Schafer, 1973; Scott et al. ms.). Several groups of microfossils, especially benthic foraminifera, have been used as indicators of both anthropogenic chemical pollution in marine environments (Alve, 1991, 1995; Alve and Olsgard, 1997; Bonetti et al. 1997; Cocciono et al. 1997; Schafer et al. 1991, 1995; Yanko,1997; Yanko et al.1998) and also naturally stressed marine environments (Kennett et al. 1997; Murray, 1997; Murray and Alve, 1997).

REFERENCES

Alve, E. 1991. Benthic foraminifera in sediment cores reflecting heavy metal pollution in Sirfjord, western Norway. Journal of Foraminiferal Research, 21: pp. 1-19.

Alve, E. 1995. Benthic foraminiferal responses to estuarine pollution: a review. Journal of Foraminiferal Research, 25: pp. 190-203.

Alve, E. and Olsgard, F. 1997. Benthic foraminiferal colonization in experiments with Cu-contaminated sediments. The First International Conference "Application

of Micropaleontology in Environmental Sciences", Tel Aviv, Israel. June 15-29, 1997. Abstract.

Asioli, A., Medioli, F.S., and Patterson, R.T. 1996. Thecamoebians as a tool for reconstruction of paleoenvironments in some Italian lakes in the foot hills of the southern Alps (Orta, Varese and Candia). Journal of Foraminiferal Research, 26(3): pp. 248-263.

Boltovskoy, E., Scott, D. B. and Medioli, F. S. 1991. Morphologic variations of benthic foraminiferal tests in response to changes in ecological parameters: a review. Journal of Paleontology, 65: pp. 175-185.

Bonetti, C, Debenay, J. P., Eichler, B. B. 1997. Deformations in benthic foraminiferal tests from a polluted Brazilian coastal system. The First International Conference "Application of Micropaleontology in Environmental Sciences", Tel Aviv, Israel. June 15-29, 1997. Abstract.

Brasier, M. D. Microfossils. George Allen & Unwin. p. 193.

CANMET, 1997. Background. Aquatic Effects Technology Evaluation (AETE) Program. Document, p. 26.

CANMET, 1997. Technical Evaluation: Water Quality and Biological Effects. Aquatic Effects Technology Evaluation (AETE) Program. Project 3.1.2. p. 46.

CANMET, 1997. AETE Annual Technical Review. Aquatic Effects Technology Evaluation (AETE) Program. (2 volumes)

Cocciono, R., Gabbianelli, G., Gentiloni, D., Silverj, P., Fonti, M. A., Kaminski, S., Monechi, F. 1997. Benthic foraminiferal response to heavy metal pollution in the

Goro Lagoon. The First International Conference "Application of Micropaleontology in Environmental Sciences", Tel Aviv, Israel. June 15-29, 1997. Abstract.

Collins, E.S., McCarthy, F.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, Paleoceanography and Taxonomy of Agglutinated Foraminifera: NATO Advanced Study Institute Series, Series C, Mathematical and Physical Sciences, 327: pp. 783-791.

Culver, S. J. 1993. Foraminifera. In: Fossil Prokaryotes and Protists. J. H. Lipps (Ed). pp. 203-248. Blackwell Scientific Publications.

Haman, D. 1982. Modern thecamoebinids (Arcellinida) from the Belize Delta, Louisiana. Transactions, Gulf Coast Association of Geological Societies, 32: pp. 353-376.

Haq, B. U. and Boersma, A. 1978. Introduction to Marine Micropaleontology. Elsevier. P. 376.

Hayward, B.W., Grenfell, H., Cairns, G., and Smith, A.,1996.Environmental controls on benthic foraminiferal and thecamoebian associations in a New Zealand tidal inlet. Journal of Foraminiferal Research, 26(2): pp.150-171.

Honig, C.A. and Scott, D.B. 1987. Post glacial stratigraphy and sea-level change in southwestern New Brunswick. Canadian Journal of Earth Sciences, 24: pp. 354-363.

Kennett, J. P., Cannariato, K. and Hendy, I. L. 1997. Foraminifera as indicators of naturally stressed environments: a Santa Barbara Basin perspective. The First International Conference "Application of Micropaleontology in Environmental Sciences", Tel Aviv, Israel. June 15-29, 1997. Abstract.

Loeb, S. L. and Spacie, A. 1994. Biological Monitoring of Aquatic Systems. Lewis Publishers, P. 381.

Loeblich, A.R. Jr. and Tappan, H. 1964a. Treatise on Invertebrate Paleontology, C: Protista 2, Sarcodina, chiefly "Thecamoebians" and Foraminiferida. In: Moore, R.C. (ed.), vol. 1 and 2, p. 900. Geological Society of America and University of Kansas Press.

Loeblich, A.R. Jr. and Tappan, H. 1964b. Foraminiferal classification and evolution. Journal of the Geological Society of India, 5: pp. 5-39.

Loeblich, A.R. Jr. and Tappan, H. 1974. Recent advances in the classification of the foraminiferida. In Foraminifera, R. H. Hedley and C. G. Adams (eds.). pp. 1-54. Academic Press.

Loeblich, A.R. Jr. and Tappan, H. 1988. Foraminiferal Genera and their Classification. Vols 1 and 2. Van Nostrand Reinhold, p. 970.

McCarthy, F.G., Collins, E.S., McAndrews, J.H., Kerr, H.A., Scott, D.B. and Medioli, F.S. 1995. A comparison of post glacial Arcellacean ("Thecamoebian") and pollen succession in Atlantic Canada, illustrating the potential of arcellaceans for paleoclimatic reconstruction. Journal of Paleontology, 69(5): pp. 980-993.

Medioli, F.S. and Scott, D.B. 1983. Holocene Arcellacea (Thecamoebians) from eastern Canada. Cushman Foundation for Foraminiferal Research Special Publication 21, p. 63.

Medioli, F.S. and Scott, D.B. 1988. Lacustrine thecamoebians (mainly Arcellaceans) as potential tools for paleolimnological interpretations. Paleogeography, Paleoclimatology, Paleoecology, 62: pp. 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: pp. 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 Advanced Study Institute Series, Series C. Mathematical and Physical Sciences, 327: pp. 813-840.

Murray, J. 1997. Foraminiferal response to environmental change. The First International Conference "Application of Micropaleontology in Environmental Sciences", Tel Aviv, Israel. June 15-29, 1997. Abstract.

Murray, J. and Alve, E. 1997. Intertidal foraminiferal production: seasonal variations in a naturally stressed environment. The First International Conference "Application of Micropaleontology in Environmental Sciences", Tel Aviv, Israel. June 15-29, 1997. Abstract.

Ogden, C. G. and Hedley, R. H. 1980. An Atlas of Fresh Water Testate Amoeba. British Museum (Natural History), Oxford University Press, p. 222.

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: pp. 14-137.

Patterson, R. T. , Barker, T. and Burbridge, S. M. 1996. Arcellaceans (Thecamoebians)as proxies of arsenic and mercury contamination in northeastern Ontario lakes. Journal of Foraminiferal Research. 26(2): pp. 172-183.

Reinhardt, E.D., Dalby, A., Kumar, A., and Patterson, R.T. 1998. Utility of arcellacean morphotypic variants as pollution indicators in mine tailing contaminated lakes near Cobalt, Ontario, Canada. Micropaleontology, 44(2): pp. 131-148.

Schafer, C. T. 1973. Distribution of foraminifera near pollution sources in Chaleur Bay. Water, Air and Soil Pollution, 2: pp. 219-233.

Schafer, C. T., Wagner, F. J. E. and Ferguson, C. 1975. Occurrence of foraminifera, mollusks and ostracodes adjacent to the industrialized shoreline of Canso Strait, Nova Scotia. Water, Air and Soil Pollution, 5: pp. 79-96.

Schafer, C. T., Collins, E. S. and Smith, J. N. 1991. Relationship of foraminifera and thecamoebian distributions to sediments contaminated by pulp mill effluent: Saguenay Fjord, Quebec, Canada. Marine Micropaleontology, 17: pp. 255-283.

Schafer, C. T., Winters, G. V., Scott, D. B., Pocklington, P., Cole, F. E. and Honig, C. 1995. Survey of living foraminifera and polychaete populations at some Canadian

aquaculture sites: potential for impact mapping and monitoring. Journal of Foraminiferal Research, 25: pp. 236-259.

Scott, D. B. and Medioli, F. S. 1983. Testate rhizopods in Lake Erie: modern distribution and stratigraphic implications. Journal of Paleontology, 57: pp. 809-820.

Scott, D. B., Reinhardt, E. G., McCarthy, F. M. G. and Patterson, R. T. (ms.) Detecting Environmental effects Using Benthic Foraminifera and Thecamoebians. p. 118.

Tappan, H. 1971. Foraminiferida. McGraw-Hill Encyclopedia of Science and Technology. pp. 467-475.

Tappan, H. and Loeblich Jr., A. R. 1969. Foraminifera, in: The Encyclopedia of Marine Resources, Frank E. Firth (ed.). Van Nostrand Reinhold Co., pp. 272-276.

Tappan, H. and Loeblich Jr., A. R. 1982. Granuloreticulosa, in: Synopsis and Classification of Living Organisms, Sybil P. Parker (ed.). vol. 1, pp. 527-552. McGraw-Hill Book Co.

Thibaudeau, S.A. and Medioli, F.S. 1986. Carboniferous thecamoebians and marsh foraminifera: new stratigraphic tools for ancient paralic deposits. Abstract. Geological Society of America, Annual Meeting, San Antonio, p. 771.

Thibaudeau, S.A., Medioli, F.S. and Scott, D.B. 1987. Carboniferous marginal-marine rhizopods: a morphological comparison with recent correspondents. Abstract, Geological Society of America, Annual Meeting, Phoenix, p. 866,

Todd, R. and Bronnimann, P. 1957. Recent foraminifera and thecamoebina from the eastern Gulf of Paria. Cushman Foundation for Foraminiferal Research. Special Publication no. 3, p. 43.

Tolonen, K. 1986. Rhizopod analysis, pp. 645-666. In. Berglund, B. E. (Ed) Handbook of Holocene Paleoecology and Paleohydrology. John Wiley.

Vasicek, M. and Ruzicka, B. 1957. Namurian Thecamoebina from the Ostrava-Karvina coal district. Sbornik Naradniho Musea v Praze, Rada B., prirodni Vedy-Acta Musei nationalis Pragae, ser. B; Historia Naturalis, 13: pp. 333-340.

Vilks, G., Schafer, C. T., and Walker, D. A. 1975. Influence of causeway on Oceanography and foraminifera in the Strait of Canso, Nova Scotia. Canadian Journal of Earth Sciences, 12: pp. 2086-2102.

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, Series 3, 13: pp. 215-245.

Warner, B. 1990. Methods in Quaternary Ecology # 5. Testate Amoebae (Protozoa). Geoscience Canada, 15(4): pp. 251-260.

Warner, B. and Buntling, M. J. 1996. Indicators of rapid environmental change in northern peat lands. In, Berger, A. R. and Iams, W. J. (eds). Geoindicators, Assessing Rapid Environmental Changes in Earth Systems. A.A. Balkema, Rotterdam. pp. 235-246.

Warner, B. G. and Charman, D. J. 1994. Holocene changes on a peat land in northwestern Ontario interpreted from testate amoebae (Protozoa) analysis. Boreas, 23: pp. 270-279.

Yanko, V. 1997. Benthic foraminifera as bioindicators of stressed environment: anthropogenic problems - foraminiferal solution. The First International

Conference "Application of Micropaleontology in Environmental Sciences", Tel Aviv, Israel. June 15-29, 1997. Abstract.

Yanko, V., Ahmad, M. and Kaminski, M. 1998. Morphological deformities of benthic foraminiferal tests in response to pollution by heavy metals: implications for pollution monitoring. Journal of Foraminiferal Research, 28: pp. 177-200.

CHAPTER 1. Use of Arcellacea (Thecamoebians) to Gauge Levels of Contamination and Remediation in Industrially Polluted Lakes

ABSTRACT

Arcellaceans are microscopic testate rhizopods found in a large number of freshwater and brackish environments. Their agglutinated shells, cemented in an organic matrix, are almost impervious to dissolution. Arcellaceans are ideal for statistical analysis because they are very abundant in Recent and late Quaternary sediments (several hundred per cc). Recent research in lakes contaminated by mine tailings in northeastern Ontario, Canada has indicated that they are sensitive indicators of a number of anthropogenic environmental factors including pH and heavy metal contamination. In particular, their asexual reproductive mode results in the production of environmentally influenced 'strains' that are particularly useful in identifying distinctive chemically polluted and remediated benthic environments in lakes. Arcellaceans have a simple morphology, making them relatively easy to identify with few taxonomic confusions. They occur in materials that are simple to prepare for examination, making them cost effective indicators of both long and short-term environmental change in lacustrine environments.

INTRODUCTION

Arcellaceans (thecamoebians) are freshwater microscopic protozoans, similar to amoebae, that form agglutinated tests, or shells. Occasionally they also occur in brackish water (< 5 ‰) environments (Todd and Brönniman, 1957; Haman, 1982; Hayward et al. 1996). Arcellacean distributional studies have been carried out over the past 150 years mainly in lakes from Europe and North America (see references in Ogden and Hedley, 1980; Tolonen, 1986). These studies were mainly of a reconnaissance nature, primarily concerned with determining the ranges of various species (see references in Medioli and Scott, 1983, 1988, and a complete thecamoebian bibliography at http://meguma.earthsciences.dal.ca/~fmedioli/intro.html).

During the past 15 years arcellacean research has shifted to concentrate more on their potential use as paleoenvironmental indicators. Their high abundance, often several hundred per cc, and excellent preservation potential in lacustrine sediments have made them useful in the reconstruction of late Quaternary-Holocene paleoenvironments (Scott and Medioli, 1983; Patterson et al., 1985; Medioli and Scott, 1988; McCarthy et al., 1995; Ellison, 1995). Arcellaceans have a generation time of only a few days. They also develop distinct morphologies in response to environmental stress. These traits have made them excellent indicators of various natural, chemically polluted and rehabilitated subenvironments within lakes affected by industrial and mining pollution (Asioli et al., 1996; Patterson et al., 1996; Kumar

and Patterson, 1997; Reinhardt et al., 1998).

TAXONOMY AND BIOLOGY

"Thecamoebians" are an artificial polyphyletic group of protozoans that includes the Order Arcellinida Kent 1880, Subclass Filosa Leidy 1879 and Order Gromida Claparede and Lachmann 1859 (Loeblich and Tappan, 1964). Thecamoebians are commonly referred to in the literature as agglutinated rhizopods or testate amoebae. The presence of pseudopodia of variable nature, an amoeboid sarcodine cell, and a very simple sac-like or cap-like test characterize them. Only a small portion of the order Arcellinida, the arcellaceans, are common in the fossil record with the majority of thecamoebians being of little paleolimnological interest (Medioli and Scott, 1983; Plate 1).

The test of thecamoebians can be secreted by the organisms themselves (autogenous tests), either proteinaceous, siliceous, or rarely calcareous. Most of the arcellacean subgroup build their tests by agglutinating foreign particles (xenosomes) in autogenous cement to form xenogenous tests. The cement in these tests is usually composed of mucopolysaccharide, highly resistant to most biological and chemical destructive agents. This test type is common in the fossil record. The nature of xenosomes is entirely controlled by the composition of the substrate, and may consist of silt grains and/or diatom frustules (Medioli et al., 1990). They have a long, albeit scanty, fossil record which goes back to the Carboniferous Period (Vasicek and Ruzicka, 1957; Thibaudeau and Medioli, 1986; Thibaudeau et al., 1987; Wightman et

al. 1994). Their fossil record is mainly from lakes (Medioli and Scott, 1988) or peat deposits (Warner, 1990; Warner and Charman, 1994; Warner and Bunting, 1996). Their small size (60-300 μm, few species are smaller than 60 μm) and high abundance make it simple to collect statistically significant populations, even from small samples.

Arcellaceans generally reproduce asexually, producing clonal offspring. However, sexuality is rare but not totally absent (Valkanov, 1962a,b, 1966; Mignot and Raikov, 1992). This reproductive strategy has led to serious taxonomic problems within the group. They have usually been grouped into specific units on the basis of test morphology (Medioli and Scott, 1983; Medioli et al., 1987), despite the fact that distinct environmentally controlled arcellacean morphotypes, or strains occur abundantly in nature. Most systematic work has thus focused on creating new 'species' of local interest. The resultant nomenclatural confusion has led to two extreme taxonomic approaches; (a) that all arcellaceans belong to the same species (Wallich, 1864) or, (b) that every morphotype that occurs more than a few times represents a genuine species (see discussion in Medioli and Scott, 1983; Medioli et al. 1987; Ogden and Hedley, 1980). Medioli et al. (1990) stated that this second approach to arcellacean taxonomy has progressed to such a degree that the vast majority of species used in the literature are so over-split that they have become useless for paleoecological purposes. As a possible solution for the taxonomic difficulties with the group Medioli and Scott (1983) proposed that arcellacean species be considered as a widely variable groups that collectively, for any given wild

population, accommodate 75% or more of the entire population. Although this species concept is subjective, it does make allowance for a substantial amount of observed morphological instability and does not preclude the identification of informally designated paleoenvironmentally useful infrasubspecific strains (Asioli et al. 1996; Reinhardt et al., 1998). This infrasubspecific level classification is quite useful for delineating large populations of arcellaceans into ecophenotypes without describing new species (Plate 1).

PALEOECOLOGICAL UTILITY

Arcellaceans occur in most areas where sufficient moisture is found (e.g. soils, mires, peat bogs, freshwater to brackish ponds and lakes etc.). Most of the lacustrine taxa prefer oligotrophic lakes with mildly acidic water, and are found in reduced numbers in eutrophic lakes (Medioli et al., 1 990). Ecological factors controlling the distribution pattern of arcellaceans include dissolved oxygen content, dystrophy-grade of the lake (C/N ratio in sediment which depends upon the existence of humus compounds), pH, the grain size of sediment, and the existence of *Sphagnum* carpet around the lake (Ellison, 1995; Tolonen, 1986).

A number of studies have used arcellaceans to identify paleoenvironmental parameters (e.g. paleohydrological changes within lakes, lake level changes, paleoclimatological changes) in late Quaternary to Recent sediments (Haman, 1982; Scott and Medioli, 1983; Patterson et al., 1985; Tolonen, 1986; Honig and Scott, 1987; Medioli and Scott, 1983, 1988; Medioli et al., 1985, 1987, and 1990, Collins et

al., 1990, McCarthy et al.1995; and Ellison, 1995; Asioli et al., 1996). Changes in arcellacean faunas also provide strong evidence of environmental changes in modern and late Quaternary peat deposits (Warner, 1990; Warner and Charman, 1994; and Warner and Bunting, 1996).

Arcellaceans are among the few benthic organisms that preserve well even in low pH freshwater sedimentary environments. Shells of other benthic organisms, like mollusks and ostracodes, dissolve in the low pH conditions typical of lake environments after the organisms die (Medioli and Scott, 1988). Other taxa commonly found in samples with arcellaceans, such as pollen grains and diatoms, are not indicative of the lake bottom environment.

ANALYTICAL METHODS

Collection and Preparation

A major advantage of working with arcellaceans lies with the very simple and inexpensive sampling and processing methodology. Methodologies for processing arcellaceans are described in detail in Medioli and Scott (1988), Medioli et al. (1990) and McCarthy et al. (1995). Our processing methods, described below, are similar but simpler (Patterson et al. 1996; Reinhardt et al., 1998).

A small boat provides an adequate sample collection platform in small lakes and ponds. We usually use an Eckman box corer but any similar sampling device is suitable. We also find that an inexpensive commercial sonar device (fish finder) equipped with bottom hardness indicator is helpful in determining appropriate

sample sites. Not only do these sonars measure water depth but with practice they can be used to distinguish rocky, muddy, or sandy substrates. Only muddy sites are sampled. Winnowed sandy substrates may have small allochthonous arcellacean communities and rocky substrates are normally barren. At each sampling station we also measure a variety of physical parameters (e.g. water depth, sedimentology, pH, water temperature, oxygen concentration, etc.) to assist us in interpreting our results. We also usually determine the geographic location of each sampling station using a Global Positioning System (GPS) unit. In very small lakes siting on nearby landmarks may provide sufficient positioning accuracy.

For distributional studies the upper 2-3 mm of sediment (arcellaceans live at the sediment-water interface (Medioli and Scott, 1988; Medioli et al. 1990) from each Eckman grab are removed to obtain a 1cc subsample for micropaleontological analysis. To avoid decay, all samples are treated with isopropyl alcohol and refrigerated immediately after collection. The samples are sieved through a 1000 μm screen to remove coarse organics, then through a 55 μm screen to retain arcellaceans and remove silts and clays.

We usually do not use biological stains (e.g. Rose Bengal) to detect living protoplasm. Due to the rapid generation time for these arcellaceans, their total populations provide a better estimate of seasonal standing crop than living populations (Scott and Medioli, 1980a).

Due to the generally large arcellacean populations in most samples, these organisms lend themselves particularly well to statistical analysis (see Fishbein and

Patterson, 1993 for recommended strategies). All micropaleontological samples are subdivided into aliquots for quantitative analysis using a wet splitter (as described by Scott and Hermelin, 1993). The subsamples may either be examined wet or dry depending on their organic content. Wet examination of organic-rich lacustrine sediments is necessary because in dried samples the vegetable debris mats together, making identification and quantitative analysis of arcellaceans nearly impossible. Wet aliquots are then examined under a binocular microscope and a statistically significant number of specimens are counted for each sample (see Patterson and Fishbein, 1989 for details).

Geochemical Analysis

The surface area of most Eckman box samplers is sufficiently large that the same grab can provide enough material for geochemical as well as micropaleontological analysis. We recommend analyzing sediment pore water rather than obtaining a bulk geochemical analysis. This is because the chemical makeup of compounds and elements found in porewater is in forms that can be generally directly ingested or absorbed by most organisms, including arcellaceans (Luoma, 1983; Campbell, 1995). The compounds and elements of the clays, silts and other solids as recorded by a bulk geochemical analysis are in forms not generally available to organisms and may suggest erroneous correlation. We recommend that samples be analyzed using the Environmental Protection Agency's method 3051: microwave digestion for inductively coupled plasma atomic emission spectroscopy

(ICP) analysis (United States Environmental Protection Agency, 1990). Additional analyses may also be carried out to measure arsenic and selenium levels using Graphite furnace atomic absorption spectroscopy (GFAAS). Cold vapor atomic absorption is used to analyze mercury levels in the samples as other metals in the ICP analysis obscure the characteristic wavelength of this element. All of these methodologies are readily available through most commercial environmental analysis firms.

CASE STUDIES

Human settlement and tourism have exerted environmental stress on lacustrine ecosystems worldwide by causing eutrophication and acidification of lake waters and their bottom sediments. Severe environmental damage has also been caused to lakes by dumping of industrial pollutants and mine tailings. We will discuss application of arcellacean micropaleontological analysis in three industrially polluted lakes in northeastern Ontario, Canada (Fig. 1 A). Two of these, Peterson and Crosswise lakes, are situated in the Cobalt region of northern Ontario. The third, James Lake lies near the town of Temagami, Ontario. The results of these studies demonstrate the potential use of arcellaceans as cost effective tools in monitoring the effects of, and rate of remediation in industrially polluted lakes.

Cobalt Area, Northeastern Ontario.

Silver was discovered at Mile 103 of the Northern Ontario Railroad during the summer of 1903 and by 1911 silver production at Cobalt Camp exceeded 30,000,000 oz. (850,000,000 g)/yr. In eight years the boomtown of Cobalt had risen out of the forest to become the worlds largest silver producer. Silver production, and the town's fortunes, began to tail off by the 1930's and by 1993 there were no active silver mines in the area (Murphy, 1977; Barnes, 1986; Dumaresq, 1993). An unfortunate legacy of the mining boom is the high level of environmental contamination of many area lakes and streams. These contaminants, primarily arsenic and mercury with significant amounts of nickel, cobalt, and cyanide, pose a significant health risk for the 10,000 people still in the area.

During mining operations waste rock and fine mill tailings were dumped in the most convenient low lying areas, usually lakes (Murphy, 1977; Barnes, 1986; Dumaresq, 1993). The silver in the ores was associated with arsenic minerals, most of which went into the tailings, and ultimately into area lakes. Huge quantities of mercury and cyanide were used in the ore milling process. These dangerous contaminants found their way into the tailings and lakes as well (Dumaresq, 1993).

Major Contaminants in the Cobalt Area

The ores in the Cobalt area contain arsenic as sulfide, sulfarsenide, and arsenide minerals. In aerobic waters, arsenate is the most common arsenic bearing solute, whereas under anaerobic conditions arsenite is common. Arsenic does not go readily into solution in the pore waters of lake sediments because it is adsorbed onto

iron and manganese oxyhydroxides (Cullen and Reimer, 1989). Due to its complex chemistry, arsenic transformations are common, resulting from changes in pH, Eh, temperature, and biological activity. Lower forms of aquatic animal life and bottom feeding fish tend to accumulate greatest amounts of arsenic. Arcellaceans, which are benthic organisms near the bottom of the food chain, are thus excellent indicators of arsenic contamination.

Mercury occurs in solid solution with native gold and silver (Berry et al. 1983) and with several sulfide minerals, particularly tetrahedrites (NRCC, 1978). Since mercury was used as an amalgam in the recovery of gold and silver, it is a very common metal in the mine tailings. Both mercury and methylmercury are available for organisms to take up and thus bioconcentration occurs, but bacterially mediated methylation is the most important bioconcentration process. The rate of methylation is pH dependent, with rates in lake water at pH 4.5 being seven times faster than at pH 8.5 (D'Itri, 1991). Once formed, methylmercury is readily absorbed by organisms and its excretion is very slow (biological half-life of mercury in fish is two years; D'Itri, 1991; CCREM, 1987). In natural aerobic waters, elemental mercury is eventually oxidized and removed from the water column by sorption onto suspended and bottom sediments (CCREM, 1987). Nonetheless, mercury has been shown to be bioconcentrated in ecosystems, and higher trophic consumers contain higher mercury concentrations than organisms lower in the food chain (Cuthbert, 1992). Therefore arcellaceans may not be very sensitive indicators of mercury contaminations.

Peterson Lake

Peterson Lake (Figure 1B) is subdivided into an eastern and a western basin by a man-made dam. The larger western basin of Peterson Lake (2.3 km^2) has a thermocline at about 8 m depth and has three distinct bathymetric areas: 1) a shallow weed-filled southern end, 2) a small shallow bay near the dam, and, 3) a deep basin in the middle. The smaller eastern basin (0.8 km^2) has a flat bottom, the result of nearly 400,000 tons of tailings deposited from the nearby Nova Scotia Mill between 1910 and 1918. Additional tailings entered the lake when a tailings dam adjacent to the Nova Scotia Mill site broke. In 1965, the eastern basin was drained and nearly 55,000 tons of tailings were removed. In the nearshore area these tailings were dredged to a depth of 9.0 m. Tailings continue to migrate into the eastern basin from leaks in containment dams adjacent to the Nova Scotia Mill site (Dumaresq, 1993; Wallis, 1993; Patterson et al., 1996, 1997).

The pH is slightly alkaline, ranging between 7 and 8. Arsenic levels measured from the substrate in the eastern basin range up to 8300 ppm and mercury levels reach 4.89 ppm, both well above acceptable levels (CCREM, 1987; Dumaresq, 1993; Patterson et al., 1996, 1997; Reinhardt et al., 1998).

Crosswise Lake

Crosswise Lake (Figure 1C) has an elongate shape in a north-south direction with an area of approximately 3.2 km^2 (Patterson et al., 1996). Fine tailings from

five different mines were dumped into the northern portion of this lake from 1905 to 1970. This dumping shortened the lake by about 300 m and reduced its depth from about 14 m to 7 m. The shallowing of the lake has produced a very flat bottom and destroyed the thermocline, in strong contrast to Peterson Lake. As in Peterson Lake the pH ranges between 7 and 8, and oxygen solubility is 11.0 ppm at the surface and 8.0 ppm at the bottom (Dumaresq, 1993; Patterson et al., 1996).

Previous studies identified mercury and arsenic as the major pollutants. Concentrations for As and Hg range up to 7100 ppm and 5.7 ppm, respectively, in the substrate. Arsenic values of up to 27.25 ppm were measured in the lake water (Dumaresq, 1993; Patterson et al., 1996; Reinhardt et al., 1998). Unfortunately, no Hg values for lake water were obtained. Pore water As and Hg concentrations from the upper most layer of the bottom sediment, where most benthic biological activity occurs, were also not obtained. However, unpublished measurements of heavy metal concentrations in nearby James Lake indicate that as would be expected pore water values are invariably much higher than in the water column. To put these levels of contamination in perspective, natural freshwater As concentrations are typically less than 2.0 ppm and the maximum acceptable concentration of As in drinking water and for aquatic life is 50.0 ppb. Background concentrations of Hg in Canadian freshwater sources are usually about 0.05 ppm. The maximum acceptable concentration of Hg in drinking water is 1.0 ppm while the maximum acceptable concentration of Hg for aquatic life is 0.1 ppm (CCREM, 1987).

Arcellacean Assemblages in Crosswise and Peterson Lakes

Several distinct arcellacean assemblages are recognized in sediment samples from these lakes, and correlate well with various distinct polluted and remediated environments. The hallmark of the most polluted environments is a dramatic reduction in diversity of arcellacean species or 'strains', with one or two clearly dominant species or strains. Arcellacean infrasubspecific strains sometimes discriminate among environments better than species units (Patterson et al., 1996; Reinhardt et al., 1998), and their use is recommended when studying lake microenvironments, pollutants, and rates of lake remediation. For example, the most highly contaminated substrate in these lakes, in the excavated trench in Peterson Lake, is dominated by *Difflugia protaeiformis* "claviformis" (Fig 1B). This strain is opportunistic and able to thrive in areas where high levels of pollutants (e.g. Hg, As, Cd, Cr, Cu, Pb in these lakes) would preclude most species. This relationship has also been observed in Italian lakes (Asioli et al., 1996). Other important indicators of hostile conditions include the centropyxids, particularly the various strains of *Centropyxis aculeata* (Fig 1B,C). Centropyxid species are capable of withstanding a variety of hostile conditions better than most other arcellacean species. These conditions include cold temperatures (Decloître, 1956), low salinities (<5 ‰; Decloître, 1953; Scott and Medioli, 1980b; Patterson et al., 1985; Honig and Scott, 1987), low nutrient levels, oligotrophic conditions (Schönborn, 1984), and sites heavily contaminated by Hg and As (Patterson et al., 1996). Hostile conditions in substrates dominated by centropyxids and *Difflugia protaeiformis* "claviformis" are

further indicated by the generally low diversity (Shannon Diversity Index values of < 0.5; defined in Fig. 2) and abundance (between 30 and 150 specimens/cc). These faunas are dominated by only one or two taxa (species and/or strains) with most species being rare. In contrast, healthy arcellacean faunas usually have Shannon Diversity Index values > 2.5 and abundances of over 500 specimens/cc. As in most stable climax communities, there is an equitable distribution of species in these healthy environments with none overwhelmingly dominating the fauna. Various strains of *Difflugia oblonga* typically characterize these assemblages.

In addition to providing easy recognition of contaminated areas of these lakes arcellacean assemblages provide data on rates of substrate remediation (Patterson et al., 1996; Reinhardt et al., 1998). The remediation of lakes contaminated by heavy metals presents unique problems. Unlike organic pollutants, such as polychlorinated biphenyl's (PCBs) and benzene compounds that can be broken down, metal pollutants are commonly in, or quickly revert to, their natural state (e.g. stable mineral form) without losing their toxicity. Thermodynamic processes dictate that stable minerals will not break down naturally to other, less toxic compounds. Possible solutions that have been suggested include the conversion of toxic metals to harmless compounds so that they would not be bioavailable. Bacterial processes can accomplish this by either reducing or oxidizing the contaminants (S2-, $CO_3$2, OH-) (Wildeman et al., 1994). Unfortunately, mine tailings sites like those at Crosswise and Peterson lakes often contain such a large amount of heavy metal pollutants that these processes are not practical and other remediation

methods need to be explored.

In Crosswise and Peterson Lakes, we observed natural remediation taking place as evidenced by the return of vegetation and "normal" arcellacean faunas in parts of the lakes (Patterson, et al., 1996; Reinhardt et al., 1998). The return of vegetation accelerates the rate of natural remediation by stabilizing cover material that in effect "caps" the tailings. For this process to occur, the pH must be relatively neutral (Forstner and Wittmann, 1981). As the lakes in the Cobalt area are alkaline, this was not an issue, but in order to remediate acidic lakes, they must be made pH neutral (e.g. by adding large quantities of lime).

An excavated trench in the eastern portion of Peterson Lake represents a subenvironment that is devoid of vegetation and is the most heavily polluted site in the lakes examined (Fig I B). Interestingly it was at this location that artificial remediation was attempted. The dredging of about 55,000 tons of sediment in 1965 disturbed the tailings that had already settled, destabilizing the pollutants and creating a subenvironment of pure tailings in contact with the lake. This procedure was not attempted in Crosswise Lake or in the western portion of Peterson Lake. In these areas the process of natural remediation is well underway and a vegetative layer is forming, or has formed, creating a barrier between the tailings and the environment (Fig 1 C). Remediation is progressing particularly well in Crosswise Lake. Despite being floored by over 7 m of contaminated tailings, the natural capping process has resulted in development of near normal arcellacean faunas in all areas except those adjacent to mine and mill operations active up until 1970.

Successful lake remediation in these and similarly polluted lakes is thus best achieved by leaving the tailings undisturbed to be buried naturally, or by speeding the process by addition of an allochthonous sediment cap. In neutral pH settings such as those found in the Cobalt area lakes, our results suggest that only a thin cap (a few mm-thick) of natural sediment and vegetative cover is required to be effective. As our arcellacean faunal analysis indicates, dredging of tailings only serves to nullify any natural remedial effects that have already occurred. In addition, when tailings are removed, a new location must be found for them, thus moving the problem elsewhere rather than solving it.

James Lake, Temagami Area, Northeastern Ontario

James Lake is a narrow, mesotrophic, "C" shaped lake located along highway 11 north of Temagami (Fig ID). The lake covers an area of 45.3 hectares, and is elongated in a north-south direction. The lake is fed by an inlet stream at the north end and drained by an outlet stream at the south end. A narrow region divides the lake into larger north (80%) and smaller south (20%) basins. The southern basin is shallow, reaching a maximum depth of only 4.0 m. The northern basin is deeper with a maximum depth of 15.0 m (Figure ID). The lake is stratified in the northern basin, with both oxygen levels and temperature dropping significantly below 5.0 m depth. During summer, temperature and oxygen levels in the upper epilimnion are 25° C and 9.0 mg/l, respectively. Temperature and oxygen concentration drops to 10° C and 2.0 mg/ l respectively in the lower hypolimnion.

The Keewatin age volcanic rocks surrounding the lake are quite rich in pyrite. Pyrite was discovered in lenses within soft green schists in 1903. The Northland Pyrite Mine Co. was operational on the southwest shore of the lake from February 1906, to March 1911, shipping more than 38,000 tons of pyrite to Cobalt, a short distance to the north. Pyrite was used for making sulfuric acid to be used for the milling of silver ore. Most waste rock (about 3,500 m^3 containing 25% pyrite) from this mine was dumped on the southwest lakeshore. Rainwater percolating through the waste rock becomes acidified and has contributed to acidification of the adjacent lake water and bottom sediments. The water flow leaches sulfates derived from the pyrite and pyrrhotite minerals. In areas near the waste rock pile sulfate concentrations in the sediment are extremely high, up to 7500 µg/g in places. The interaction between these sulfate ions and hydrogen ions from water produces sulfuric acid. In addition, localized bacterial reduction of some sulfate to H_2S may contribute to development of a toxic benthic environment for many aquatic invertebrates (Environment Canada, 1979). At the times of sampling there was a gradual change from a low of pH (2.0) in some bottom sediments adjacent to the waste rock piles to almost neutral conditions (pH 6.8) in more distant areas of the southern basin of the lake. The situation of the outlet stream adjacent to the mine site and the overall north south flow of water in the lake help maintain this gradient.

Several metals, most notably Fe and Al, are being leached out of the waste rock. Sediment pore water iron levels vary from a low of 1.52 mg/l in the northern basin to a high of 11,800 mg/l near the waste rock pile. Iron concentration in lake

water varies from 0.09 mg/l in the northern basin to 2.4 mg/l near the waste rock pile (Gale, 1990). During freshet and particularly during spring turnover the pH of the lake water rises to nearly neutral values throughout the lake (Gale, 1990). When the acidic, metal-laden water near the waste dump mixes with the neutral water of the rest of the lake the metal precipitates out as iron hydroxide (FeOH). All measured pore water and lake water iron concentrations were found to be well in excess of the maximum value (0.3 mg/l) set by provincial drinking water guideline (CCREM, 1987). Iron is so plentiful in the environment that very high levels often accumulate in invertebrates. Since iron is an essential trace element, a certain amount of bioconcentration can occur with little ill effect (Vymazal, 1984; Tessier et al., 1984). The low drinking water guideline/standard is based more on aesthetics than on health concern. The taste of iron can readily be detected at 1.8 mg/l and high concentrations also lead to staining of laundry and plumbing and massive growth of bacteria in water systems (Moore, 1991). The recommended daily intake for men is 10 mg and 18 mg for women. The daily intake of iron from drinking water containing 0.3 mg Fe/l would be only 0.6 mg. Both Gale (1990) and ourselves observed a large number of vertebrates (fish and amphibians) in the lake, although mostly in the eastern part of the southern basin. Although guidelines for the protection of aquatic life range from 0.3 mg/l to 1.0 mg/l the tolerance of these organisms seems to be much higher (>10 mg/l; Moore, 1991).

Aluminum concentrations in pore water varied from 0.19 mg/l to 415 mg/l near the waste rock pile. Aluminum values in the lake water itself varied from 0.05

mg/l in the northern basin to 0.24 mg/l near the waste rock pile (Gale, 1990). Aluminum is not essential for survival but is found in virtually all plant and animal species. In higher pH regimes aluminum complexes into relatively stable complexes (Plankey and Patterson, 1987, 1988). However, in lower pH environments (<pH 5.5), such as found in the southern basin of James Lake, it mobilizes into biologically useable forms (Burrows, 1977). The guidelines for control of aluminum are highly variable and reflect differing opinions on the hazard posed by aluminum in drinking water but 0.2 mg/l seems to be the maximum allowable concentration agreed to by most agencies (Moore, 1991). The guidelines for the protection of aquatic life in Canada and several European nations are 0.005 mg/l at pH<6.5 and 0.1 mg/l at pH >6.5.

Arcellacean Assemblages in James Lake

James Lake provides an ideal laboratory for assessing the sensitivity of arcellaceans to industrial pollutants (Kumar and Patterson, 1997). The flow of lake water from north to south, exiting near the pollution point source at the old mine site, has created habitats that range from unimpacted in the northern basin to extremely contaminated near the mine site itself. Furthermore, the low pH environment at James Lake provides an instructive contrast to the near neutral pH lakes of the Cobalt area. While both areas are contaminated by toxic heavy metals, the different acidity levels are reflected in the respective arcellacean faunas.

Arcellacean faunas in James Lake mirror the highly contaminated low pH

areas quite well. The highly Fe and Al contaminated, acidic areas of the lake (pH 2.0 to 5.5), adjacent to the mine waste rock pile are characterized by low diversity faunas with Shannon Diversity Index values of generally t< 1.0 and an average of less than 6 species per sample. In higher pH areas (pH 6.5-7.5) where the level of contamination was low the Shannon Diversity Index increased dramatically to 1.5-2.5 with most values greater than 2.0 (Fig. 2).

The distribution of individual taxa in James Lake indicate that pH, rather than Fe and/or Al concentration, may be the dominant factor controlling arcellacean faunas in the lake. *Arcella vulgaris* is the dominant species (90-100 %) in the most contaminated areas at < pH 5.5, and forms < 5 % of the total assemblage (or it is totally absent) in the less contaminated regions at pH between 6.5-7.5 (Fig. 2). *Arcella vulgaris* is an important component of arcellacean faunas in boggy ponds in the Arctic and further south (Collins et al. 1990). The low pH typical of these ponds has preadapted this species to dominate similar low pH environments. Other indications that pH may be the dominant controlling factor on arcellacean distribution is the notable absence of opportunistic centropyxid taxa. In higher pH environments in the Cobalt area species such as *Centropyxis aculeata* dominate contaminated substrates (Patterson, et al., 1996; Reinhardt et al., 1998). Also notably missing from the lower pH environments of this lake are any strains of *Difflugia protaeiformis*, although the species is often abundant in portions of James Lake with pH of 6.5-7.5, and in higher pH and highly contaminated areas of Peterson and Crosswise lakes.

In the higher pH environments of the lake there is a greater abundance and diversity of arcellacean species and phenotypes, although, as found in most northern lakes, various strains of *Difflugia oblonga* usually dominate (25-50%; Fig. 2). Other taxa, such as *Difflugia corona*, *Lesquereusia spiralis*, *Difflugia urceolata* and *Difflugia protaeiformis*, also occur significantly (10-50%) at pH 6.5-7.5, and do not occur in this lake at < pH 5.5. The highly variable proportion of the other arcellacean taxa recorded in higher pH areas of James Lake reflect the presence of a variety of subenvironments not discussed here (Fig. 2; Patterson and Kumar, unpublished data).

Paleolimnological Analysis at James Lake

A major impetus for research in the James Lake area was concern by local area cottagers and wilderness outfitters that ongoing contamination from the site was having an adverse effect on the environment. Although it is obvious that mining activity has had an adverse effect on the lake, some key information must be obtained before an effective ecosystem management plan for James Lake can to be put in place. This information includes knowledge of baseline conditions and natural variability, identification of the time when conditions in the lake first began to change, and a determination of possible outcomes (Ford, 1988). This information includes a temporal component and thus requires long- term data so that realistic targets for remediation efforts can be set, anthropogenic activity can be discerned and measured, and future scenarios inferred (Likens, 1988; Elliot, 1990; Smol, 1992). For a situation like that at James Lake, aquatic ecosystem managers generally choose

from four main sources of data to address the objectives above. These include direct historical measurements, space-for-time substitution (i.e. comparing chemistry and biota in similar but unaffected lakes), computer models based on empirical or dynamic data, and paleolimnological constructions (Smol, 1992).

At James Lake, as with most lakes, direct historical measurements are rarely available for the time-frame of interest. Due to the unusual configuration of the lake and position of the pollution source with regard to the outlet, a comparative approach was possible within the lake itself. Both geochemical analysis and the observed arcellacean faunas indicate a highly contaminated area adjacent to the old mine site, and it is obvious that mining activity has seriously impacted the lake. However, according to the requirements for effective aquatic management, a determination of baseline conditions must be made prior to any remedial action.

Paleolimnological methods are the best approach for determining baseline conditions. Unfortunately, except where the sediment sink is large and stable, geochemical methods do not always provide an accurate depiction of the historical record (Horowitz, 1991; Bethke, 1996). Preservable micropaleontological bioindicators such as arcellaceans are thus the best tools to make a temporal assessment of the history of pollution and/or remediation of the contaminated area. Microfossils, except in areas of excessive bioturbation, do not migrate and they archive data on scales varying from millennia to single seasons, providing invaluable information to ecosystem managers.

Our paleolimnological analysis is based on a 1 m core obtained from the

lake bottom sediments adjacent to the waste rock site (Fig. ID). The upper 30 cm of the core are dominated by *Arcella vulgaris* faunas in both a black organic rich unit and iron stained sediment (top 18 cm), indicating deposition under low pH and probably highly contaminated conditions Lower intervals of the core are dominated by centropyxids indicating environmentally stressed but higher pH conditions. The high abundances of the seasonally floating arcellacean *Cucurbitella tricuspis* (Schönborn, 1984) in most samples is the result of current transport unrelated to substrate conditions at the core site. Prior to obtaining ^{14}C dates it was assumed that the rise of the *Arcella vulgaris* dominated fauna coincided with the initiation of mining activity and lake acidification. As the average sedimentation rate in lakes varies between 1 and 5 mm per year (Förstner and Wittman, 1983; Kukal, 1971) we assumed that the interval dominated by *Arcella vulgaris* was deposited since mine activity began. However, seven ^{14}C dates obtained from three cores, one collected less than one metre from the one studied here, indicates that sedimentation rate in the area of the lake adjacent to the mine site has been very low for at least the past 9000 years (Mason, 1998). Low pH, contaminated conditions have thus characterized the site for over 2000 years, and this site was a stressed environment for several thousand years prior to that. Thus natural acidification of the site, from sulfates leaching from naturally exposed large pyrite veins, began long before any anthropogenic contribution. This is not an unusual occurrence as any area characterized by metal-bearing formations will have values of those metals occurring at elevated levels (see Förstner and Wittman, 1983 for examples). Detection of these elevated levels is a

major exploration tool used by mineral exploration companies searching for ore. However, this reality is often unknown to environmental scientists who have not had geological training who may assume that any elevated contaminant levels in an area is anthropogenic. In the case of James Lake it seems that the most grievous damage caused by the mining activity concerns aesthetics and safety, the result of huge piles of unsightly waste rock, deep shafts, and fallen down head frames. Although mining may have exacerbated pollution in an already highly contaminated and acidified environment the pollution was clearly present already. Geochemical analysis of cores in the area provide corroborative evidence that elevated levels of Fe, Al, and sulfate have existed for thousands of years at this site (Mason, 1998).

SUMMARY

Arcellaceans are sensitive to a whole host of natural and anthropogenic environmental factors including pH and heavy metal contamination, and as such are excellent bioenvironmental indicators. Because of their asexual reproductive mode, the generation of environmentally induced phenotypes is particularly useful in identifying various chemically polluted and remediated benthic environments in lakes. Unlike other lacustrine bioindicators such as mollusks and ostracodes, arcellaceans preserve well in the generally lower pH conditions found in lakes and thus are useful to track paleolimnological conditions on scales varying from millennia to single seasons. They are also very abundant with several hundred specimens being found per cc, making them ideal for statistical analysis.

ACKNOWLEDGMENTS

NSERC Research Grant OGP 0041665 TO RTP supported this research. We gratefully acknowledge the assistance of students in the Department of Earth Sciences Environmental Geology Field Camp (67.285) for their help in the field.

REFERENCES

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(3): 248-263.

Barnes, M., 1986. Fortunes in the ground: Cobalt, Porcupine and Kirkland Lake. Boston Mills Press, Erin, Ontario. 263 p. Berry, L. G., Mason, B. and Dietrich, R. V., 1983. Mineralogy. W. H. Freeman and Company, San Francisco, 561 P.

Bethke, C.M., 1996. Geochemical Reaction Modelling. Oxford University Press, Inc. New York, NY. 397 p.

Burrows, W. D., 1977 . Aquatic aluminum: chemistry, toxicology and environmental prevalence. CRC Crit. Rev. Environ. Control, 7: 167-216.

Campbell, P.G.C., 1995. Interactions between trace metals and aquatic organisms: a critique of the free-ion activity model. In: Metal Speciation and Bioavailability in Aquatic Systems. A. Tessier, and D.R. Turner (eds.) John Wiley & Sons Ltd.

CCREM, 1987. Canadian water quality guidelines: Task Force on Water Quality

Guidelines of the Canadian Council of Resource and Environment Ministers (no page reference).

Claparède, E. and Lachmann, J., 1859.Etudes sur les infusoires et les rhizopodes. Tome I (2me partie): Memoires de l'Institut National Genevois, 6 (for 1858): 261-242.

Collins, E.S., McCarthy, F.M., Medioli, F.S., Scott, D.B. and Honig, C.A., 1990. Biogeographic distribution of modern thecamoebians in a transact along the eastern North American coast, in Hemleben, C., Kaminski, M.A., Kuhnt, W. and Scott, D.B. eds., Paleoecology, Biostratigraphy, Paleoceanography and Taxonomy of Agglutinated Foraminifera: NATO Advanced Study Institute Series, Series C, Mathematical and Physical Sciences, 327:783-791.Cullen, W. R. and Reimer, K. J., 1989. Arsenic speciation in the environment. Chemical Reviews, 89:713-764.

Cuthbert, I. D., 1992. A regional assessment of mercury contamination in yellow perch *(Percaflavescens)* in Ontario: implications for common loons *(Gavia immer).* in Niimi, A. J. and Taylor, M. C. (Editors), Proceeding of the eighteenth Annual Aquatic Toxicology Workshop, September 30- October, 3 1991. Ottawa, Ontario. pp. 87-97.

Decloître, L., 1953. Recherches sur les Rhizopodes thecamoebiens d'A.O.F. (Suite). Faune du Lac Tamna (Senegal): Bulletin de l'Institut Franc,ais d'Afrique Noire, no. 31:249.

Decloître, L., 1956. Les thecamoebiens de l'Eqe (Groenland): Expeditions Polaires

Francaises Missions Paul-Emile Victor VIII, Actualites Scientifiques et Industrielles 1242, 100p.

Deltapoint, 1996. Deltagraph User's Guide. Monterey, CA.

D Itri, E. M. 1991. Mercury contamination- what we have learned since Minimata: Environmental Monitoring and Assessment, 19: 165-182

Dumaresq, C. G., 1993. The occurrence of arsenic and heavy metal contamination from natural and anthropogenic sources in Cobalt area of Ontario. Unpub. M.Sc. thesis, Carleton University and Ottawa Carleton Geoscience Centre, Ottawa. 326 P.

Elliot, J.M., 1990. The need for long-term investigation in ecology and the contributions of the Freshwater Biological Association. Freshw. Biol. 23:1-5.

Ellison, Robert L. 1995. Paleolimnological analysis of Ullswater using testate amoebae. Paleolimnology, 13: 51 -63.

Environment. Canada, 1979. Water Quality Source Book.

Fishbein, E. and Patterson, R. T., 1993. Error-weighted maximum likelihood (EWML): a new statistically based method to cluster quantitative micropaleontological data. Journal of Paleontology, 67(3):475-485.

Ford, J., 1988. The effects of chemical stress on aquatic species composition and community structure. In: S.A. Lewin, M.A. Harwell, J.R. Kelly and K.D. Kimball (eds.), Ecotoxicology: Problems and Approaches, p 99-144. Springer-Verlag, New York.

Forstner, O., and Wittmann, G.T.W., 1983. Heavy metals in industrial and domestic

effluents, Chapter G2 *in* Metal Pollution in the Aquatic Environment. Heidelberg, Germany: Springer-Verlag, 340-351.

Gale, P., 1990. James Lake, Northland Pyrite Mine. Ontario Department of the Environment Technical Memorandum. Sudbury Ontario. 15 p.

Haman, D., 1982. Modern Thecamoebinids (Arcellinida) from the Belize Delta, Louisiana. Transactions, Gulf Coast Association of Geological Societies, 32: 353-376.

Hayward, B.W., Grenfell, H., Cairns, G., and Smith, A., 1996. Environmental controls on benthic foraminiferal and thecamoebian associations in a New Zealand tidal inlet. Journal of Foraminiferal Research, 26(2): 150- 171.

Honig, C.A. and Scott, D.B., 1987. Post glacial stratigraphy and sea-level change in southwestern New Brunswick. Canadian Journal of Earth Sciences, 24: 354-363.

Horowitz, A.J., 1991. A primer on Sediment-Trace Element Chemistry, 2nd rev. ed. Lewis Publishers, Inc. Chelsea, Michigan. 136 p.

Kent, W. S., 1880. A manual of the Infusoria; including a description of all known flagellate, ciliate and tentaculiferous Protozoa, British and foreign, and an account of the organization and affinities of the sponges. 1, 472 p., D. Bogue, London.

Kukal, Z., 1971. Geology of Recent Sediments. Academic Press Inc., London, 490 p.

Kumar, A. and Dalby, A.P., 1998. Identification key for Holocene lacustrine arcellacean (thecamoebian) taxa. Palaeontologia Electronica, 1(1): 39 p.

Kumar, A., and Patterson, R. T., 1997. Arcellaceans (Thecamoebians) as proxies of lake bottom acidity: an example from James Lake, northeastern Ontario. Geological Association of Canada/ Mineralogical Association of Canada Annual Meeting, May 1921, 1997. (Abstract), p. A- 150.

Leidy, J. 1879. Fresh water rhizopods of North America. Unites States Geological Survey of the Territories, Report 12, 1-324.

Likens, G.E. (ed.), 1988. Long term studies in ecology: Approaches and alternatives. Springer-Verlag, New York. 214 p.

Loeblich, A R. Jr. and Tappan, H., 1964. Sarcodina, chiefly "Thecamoebians" and Foraminiferida. In: Moore, R. C. ed., Treatise on Invertebrate Paleontology, Part C. Protista II, 1:1 -510. Geological Society of America and University of Kansas Press.

Luoma, S.N.1983. Bioavailability of trace metals to aquatic organisms—a review. Science of the Total Environment, 28:1 -22.

Mason, G. 1998. A study of the effects of past mining activities on James Lake sediment Chemistry, Carleton University Department of Environmental Science, Unpublished Honors Thesis, 53 p.

McCarthy, F.G., Collins, E.S., McAndrews, J.H., Kerr, H.A., Scott, D.B. and Medioli, F.S., 1995. A comparison of post glacial Arcellacean ("Thecamoebian") and pollen succession in Atlantic Canada, illustrating the potential of arcellaceans for paleoclimatic reconstruction. Journal of Paleontology, 69(5):980-993.

Medioli, F.S. and Scott, D.B., 1983. Holocene Arcellacea (Thecamoebians) from eastern Canada. Cushman Foundation for Foraminiferal Research Special Publication 21, 63p.

Medioli, F. S., Petrucci, F. and Scott, D. B., 1985. Sulla presenza di Tecamebe in campioni carotati sul fondo del Lago di Garda (missione Picard, sett. 1981): Civiltà Gardesana, v. 3: "L'ambiente Lago", pp. 83-103.

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. and Scott, D.B., 1988. Lacustrine thecamoebians (mainly Arcellaceans) as potential tools for paleolimnological interpretations. Paleogeography, Paleoclimatology, Paleoecology, 62: 361-386.

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 Advanced Study Institute Series, Series C. Mathematical and Physical Sciences, 327: 813- 840.

Mignot, J. P. and Raikov, I. B. 1992. Evidence for meiosis in the testate amoeba *Arcella*. Jour. of Protozoology, 39: 287-289.

Moore, J.W., 1991. Inorganic Contaminants of Surface Water: Research and Monitoring Priorities. New York: Springer-Verlag, 334p.

Murphy, J. P., 1977. Yankee Takeover of Cobalt: Highway Bookshop Press, Cobalt, Ontario. 200 P.

NRCC, 1978. Effects of arsenic in the Canadian environment: National Research Council of Canada, No. 15391, Associate Committee on Scientific Criteria for Environmental Quality, Ottawa, Ontario, Canada. P. 349.

Ogden, C. G. and Hedley, R. H., 1980. An Atlas of Fresh Water Testate Amoeba. British Museum (Natural History), Oxford University Press, 222p.

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: 14-137.

Patterson, R.T. and Fishbein, E., 1989. Re-examination of the statistical methods used to determine the number of point counts needed for micropaleontological quantitative research. Journal of Paleontology, 63: 245-248.

Patterson, R. T., Barker, T. and Burbridge, 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., Kumar, A., and Dumaresq, C, 1997. Arcellaceans: shelled microinvertebrates as cost-effective tools for monitoring current and historical environmental trends. 24th Annual Aquatic Toxicity Workshop, Niagara Falls, Ontario, October 19-22, 1997.(Abstract).

Plankey, B. J. and Patterson, H. H.,1987. Kinetics of aluminum fulvic acid

complexation in acidic waters. Environmental Science & Technology, 21: 595-601.

Plankey, B. J. and Patterson, H. H., 1988. Effect of fulvic acid on the kinetics of aluminum fluoride complexation in acidic waters. Environmental Science & Technology, 22:1454-1456.

Reinhardt, E.D., Dalby, A., Kumar, A., and Patterson, R.T., 1998. Utility of arcellacean morphotypic variants as pollution indicators in mine tailing contaminated lakes near Cobalt, Ontario, Canada. Micropaleontology, 44 (2).

Schönborn, W.S., 1984. Studies on remains of Testacea in cores of the Great Woryty Lake (NE-Poland). Limnologica (Berlin), 16: 185- 190.

Scott, D.B., and Medioli, F.S., 1980a. Living vs. total foraminiferal populations; their relative usefulness in paleoecology. Journal of Paleontology. 54:814-831.

Scott, D.B., and Medioli, F.S., 1980b. Post-glacial emergence curves in the Maritimes determined from marine sediments in raised basins: Proceedings of Coastlines '80. National Science and Engineering Research Council, 428-449.

Scott, D. B. and Medioli, F. S. 1983. Testate rhizopods in Lake Erie: modern distribution and stratigraphic implications. Journal of Paleontology, 57: 809-820.

Scott, D. B. and Hermelin, J. O. R., 1993. A device for precision splitting of micropaleontological samples in liquid suspension. Journal of Paleontology. 67: 151154.

Smol, J.P. 1992. Paleolimnology: an important tool for effective ecosystem

management. Journal of Aquatic Ecosystem Health 1: 49-58.

Tessier, A., Campbell, P. G. C., Auclair, J. C. and Bisson, M., 1984. Relationships between the partitioning of trace metals in sediments and their accumulation in the tissues of the fresh water mollusk *Elliptio complanata* in a mining area. Canadian Journal of Fisheries & Aquatic Sciences, 41: 1463-1472.

Thibaudeau, S.A. and Medioli, F.S. 1986. Carboniferous thecamoebians and marsh foraminifera: new stratigraphic tools for ancient paralic deposits. Abstract. Geological Society of America, Annual Meeting, San Antonio, p. 771.

Thibaudeau, S.A., Medioli, F.S. and Scott, D.B. 1987. Carboniferous marginal-marine rhizopods: a morphological comparison with recent correspondents. Abstract, Geological Society of America, Annual Meeting, Phoenix, p. 866.

Todd, R. and Brönnimann, P., 1957. Recent foraminifera and thecamoebina from the eastern Gulf of Paria. Cushman Foundation for Foraminiferal Research Special Publication no. 3, 43 p.

Tolonen, K., 1986. Rhizopod analysis, p. 645-666. In. Berglund, B. E. (ed) Handbook of Holocene Paleoecology and Paleohydrology. John Wiley, New York.

United States Environmental Protection Agency, 1990. Test Methods for Evaluating Solid Waste. Third Edition. SW-846, 3051 - 1 - 3051 - 13.

Valkanov, A., 1962a. Uber de Kopulation der Testaceen (Rhizopoda-Testacea): Reports of the Bulgarian Academy of Science, 15(3): 305-308.

Vasicek, M. and Ruzicka, B. 1957. Namurian Thecamoebina from the Ostrava-Karvina coal district. Sbornik Naradniho Musea v Praze, Rada B., prirodni Vedy-Acta Musei nationalis Pragae, ser. B; Historia Naturalis, 13: pp. 333-340.

Volkanov, A. 1962b. *Paraquadrula madarica* n sp. (Rhizopoda-Testacea): Reports of the Bulgarian Academy of Science, 15(4): 423-426.

Vilkanov, A. 1966. Uber die Fortpflanzung der Testaceen (Rhizopoda-Testacea): Bulgarian Academy of Science, Bulletin of the Institute and Museum of Zoology (Sofia). 22: 5-4

Vymazal, J. 1984. Short term uptake of heavy metals by periphyton algae. Hydrobiologia, 119: 171-179.

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, Series 3, 13: 215-245.

Wallis, S. D., 1993. Sonar profiling: a subbottom study of Gillies, Peterson and Crosswise lakes, Ontario. Unpublished B.Sc. thesis, Carleton University, Ottawa, Ontario, P40.

Warner, B., 1990. Methods in Quaternary Ecology # 5. Testate Amoebae (Protozoa). Geoscience Canada, 15(4): 251-260.

Warner, B. G. and Charman, D. J., 1994. Holocene changes on a peat land in northwestern Ontario interpreted from testate amoebae (Protozoa) analysis. Boreas, 23: 270-279.

Warner, B. and Bunting, M. J., 1996. Indicators of rapid environmental change in northern peat lands. In, Berger, A. R. and Iams, W. J. (eds). Geoindicators,

Assessing rapid environmental changes in earth systems. A.A. Balkema, Rotterdam. 235-246.

Wightman, W.G., Scott, D.B. Medioli, F.S. and Gibling, M.R., 1994, Agglutinated foraminifera and thecamoebians from the Late Carboniferous Sydney coalfield, Nova Scotia: paleoecology, paleoenvironments and paleogeographical implications: Paleogeography, Paleoclimatology, Paleoecology, v.106, p.187-202.

Wildeman, T.R., Updegraff, D.M., Reynolds, J.S., and Bolis, J.L., 1994. Passive bioremediation of metals from water using reactors or constructed wetlands *in* Means, J.L., and Hinchee, R.E. (eds.), Emerging Technology for Bioremediation of Metals. Boca Raton, Florida: CRC Press, 13-25.

Wilkinson, L., 1992. SYSTAT: Statistics Version 5.2 Edition. Evanston, IL.: SYSTAT, Inc. P 724.

Figures in Text

Figure 1. A. Location Map showing position of studied lakes in northeastern Ontario. B. Map of Peterson Lake in the Cobalt area showing general pH, bathymetry, location of mines and mills, as well as areas inhabited by various arcellacean faunas, particularly the *Difflugia protaeiformis* "claviformis" dominated fauna found in the highly contaminated excavated trench. C. Map of Crosswise Lake in the Cobalt area showing general pH, bathymetry, location of mines and mills as well as areas inhabited by various arcellacean faunas, particularly areas of the lake showing clear indication of remediation. D. Map of James Lake in the Temagami area showing general pH, bathymetry, location of the pyrite mine, core site, and areas inhabited by the low pH indicating *Arcella vulgaris* fauna.

Figure 2. Relative proportion of various taxa, and Shannon Diversity Index in relation to pH in James Lake. The linear least squares method was used to determine the best fit for the linear curve fits using Deltagraph 4.0 (Deltapoint, 1996). The Shannon Diversity Index $H(S) = -p_i * \ln(p_i)$ where p_i is the proportion of the i^{th} species (and/or strains) in the assemblage. Shannon Diversity Index is a better measure of diversity than numbers of species because it also takes into account the relative proportions of species (equitability) in the population.

Figure 3. Sedimentology, biostratigraphy and ^{14}C dates from a core collected in James Lake adjacent to the waste rock pile. The ^{14}C date was obtained from a core collected for geochemical analysis (Mason, 1998) less than one m away.

Figure 1

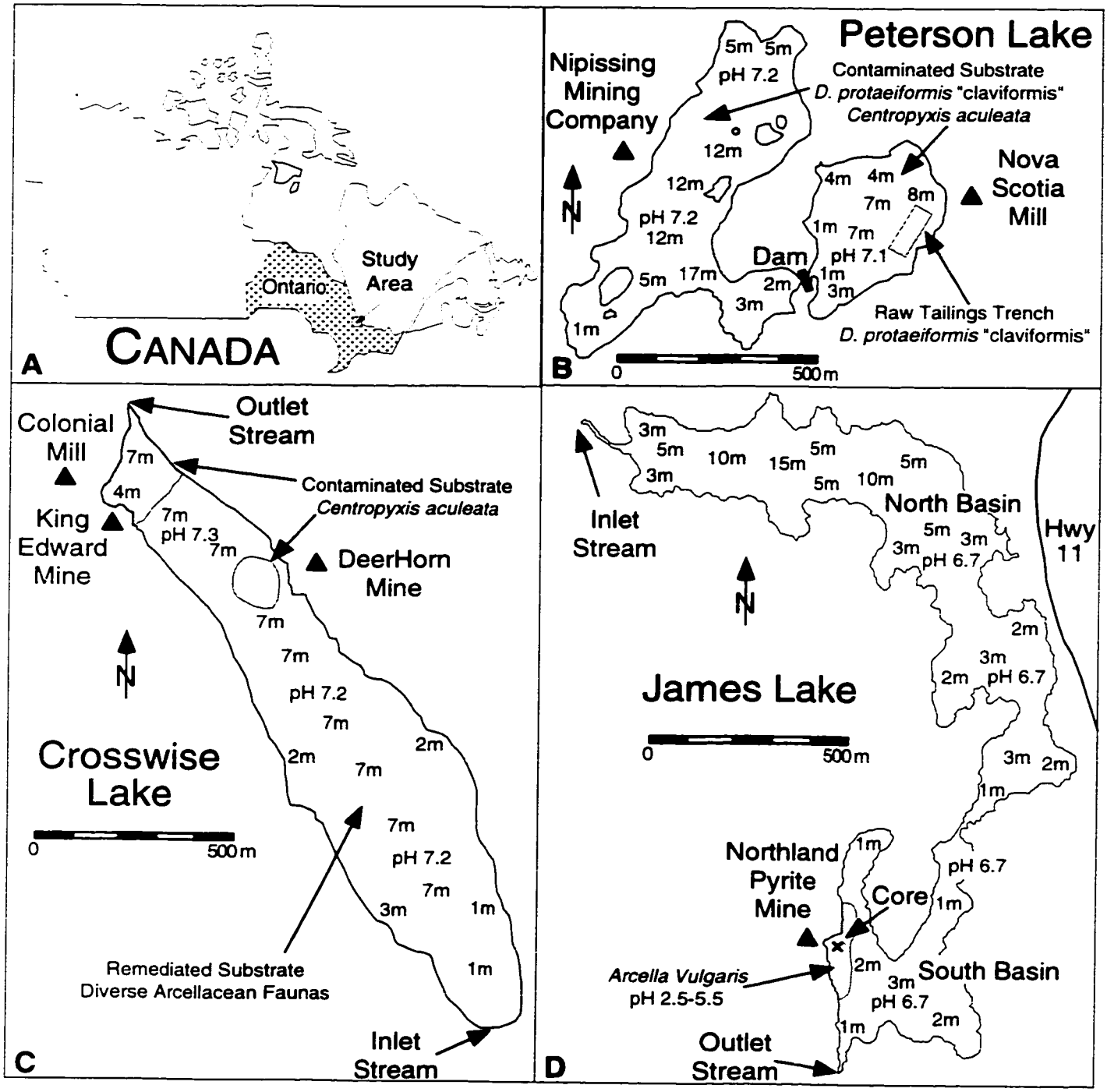

A
CANADA
Ontario
Study Area
B
Peterson Lake
Nipissing Mining Company
Contaminated Substrate
D. protaeiformis "claviformis"
Centropyxis aculeata
Nova Scotia Mill
Dam
Raw Tailings Trench
D. protaeiformis "claviformis"
pH 7.2
pH 7.1
0
500m
C
Colonial Mill
Outlet Stream
Contaminated Substrate
Centropyxis aculeata
King Edward Mine
DeerHorn Mine
pH 7.3
pH 7.2
Crosswise Lake
0
500m
Remediated Substrate
Diverse Arcellacean Faunas
Inlet Stream
D
Inlet Stream
North Basin
Hwy 11
James Lake
0
500m
Northland Pyrite Mine
Core
Arcella Vulgaris
pH 2.5-5.5
South Basin
pH 6.7
Outlet Stream

Figure 2

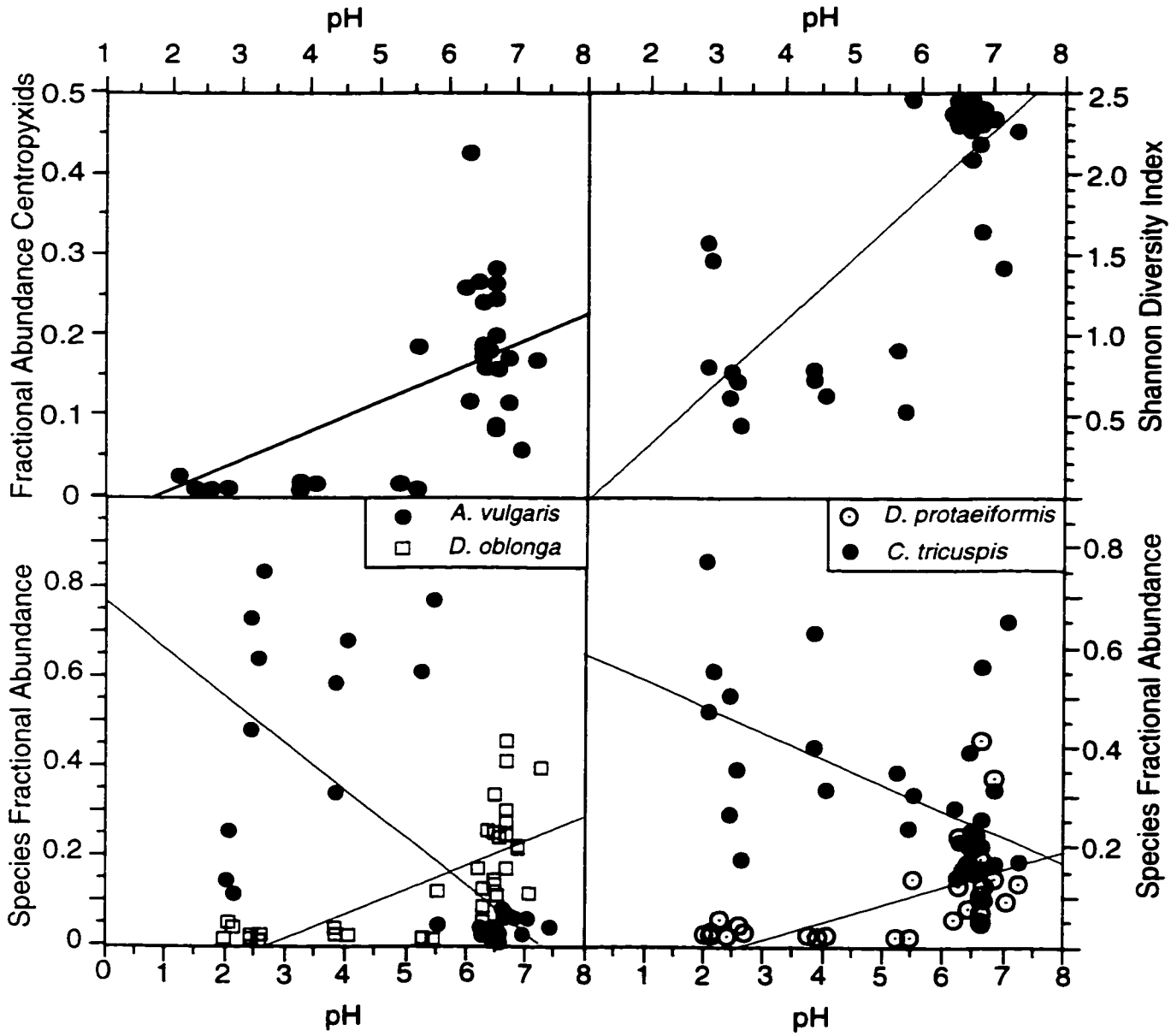
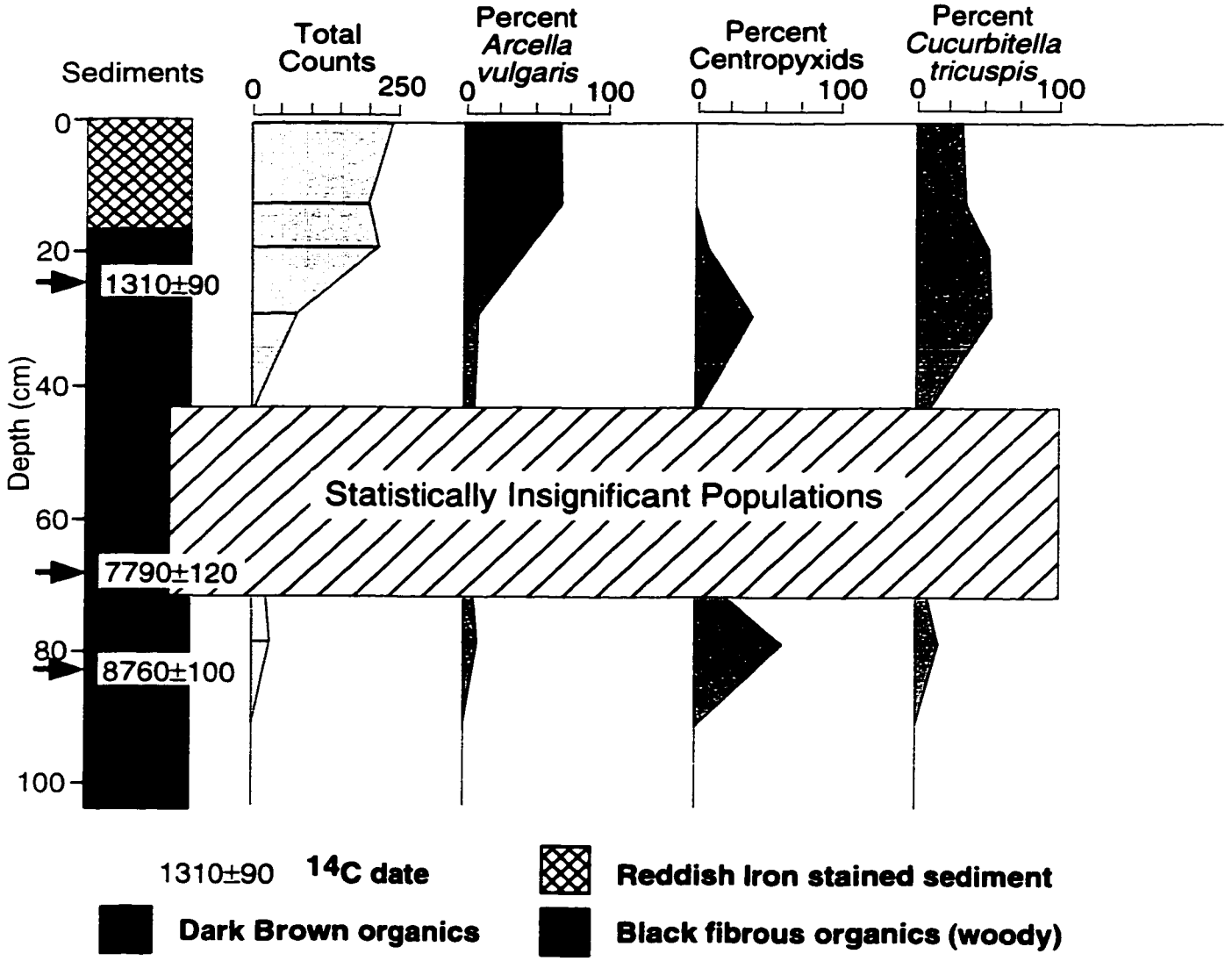

pH
Fractional Abundance Centropyxids
Shannon Diversity Index
Species Fractional Abundance
A. vulgaris
D. oblonga
D. protaeiformis
C. tricuspis

Figure 3


Sediments
Total Counts
0
250
Percent Arcella vulgaris
0
100
Percent Centropyxids
0
100
Percent Cucurbitella tricuspis
0
100
Depth (cm)
0
20
40
60
80
100
1310±90
7790±120
8760±100
Statistically Insignificant Populations
1310±90 14C date
Reddish Iron stained sediment
Dark Brown organics
Black fibrous organics (woody)

Photoplate 1

1. *Difflugia bacillariarum* Perty 1849 (size 100 microns, specimen from Lake Erie)
2. *Centropyxis aculeata* Ehrenberg 1832, strain "discoides" Reinhardt et al. 1998 (size 160 microns, specimen from Lake Sentani, Irian Jaya, Indonesia)
3. *Difflugia fragosa* Hempel 1898 (size 156 microns, specimen from Lake Erie)
4. *Difflugia bidens* Penard 1902 (size 160 microns, specimen from Swan Lake, north of Toronto, Ontario)
5. *Difflugia urens* Patterson et al. 1985 (size 176 microns, specimen from Midway Lake, Nova Scotia)
6. *Pontigulasia compressa* Carter 1864 (size 126 microns, specimen from Lake Erie)
7. *Arcella vulgaris* Ehrenberg 1830 (size 124 microns, specimen from Crosswise Lake near Cobalt, Ontario)
8. *Difflugia urceolata* Carter 1864, strain "urceolata" Reinhardt et al. 1998 (size 160 microns, specimen from Peterson Lake near Cobalt, Ontario)
9. *Lagenodifflugia vas* Leidy 1874 (size 90 microns, specimen from Peterson Lake near Cobalt, Ontario)
10. *Lesquerausia spiralis* Ehrenberg 1840 (size 93 microns, specimen from Peterson Lake near Cobalt, Ontario)
11. *Centropyxis aculeata* Ehrenberg 1832 strain "aculeata" Reinhardt et al. 1998 (size 135 microns, specimen from Crosswise Lake near Cobalt, Ontario)
12. *Centropyxis constricta* Ehrenberg 1843, strain "constricta" Reinhardt et al. 1998 (size 150 microns, specimen from Crosswise Lake near Cobalt, Ontario)

13. *Centropyxis constricta* Ehrenberg 1843 strain "aerophila" Reinhardt et al. 1998 (size 108 microns, specimen from Peterson Lake near Cobalt, Ontario)

14. *Cucurbitella tricuspis* Carter 1856 (size 95 microns, specimens from Peterson Lake near Cobalt, Ontario)

15. *Difflugia corona* Wallich 1864 (size 120 microns, specimen from Peterson Lake near Cobalt, Ontario)

16. *Difflugia globula* Ehrenberg 1848 (size 225 microns, specimen from Crosswise Lake near Cobalt, Ontario. The species name "globulus" was changed to "globula" by Kumar and Dalby, 1998)

17. *Difflugia oblonga* Ehrenberg 1832 strain "oblonga" Reinhardt et al. 1998 (size 104 microns, specimen from Crosswise Lake near Cobalt, Ontario)

18 *Difflugia oblonga* Ehrenberg 1832 strain "tenuis" Reinhardt et al. 1998 (size 120 microns, specimen from Crosswise Lake near Cobalt, Ontario)

19. *Difflugia oblonga* Ehrenberg 1832 strain "triangularis" Reinhardt et al. 1998 (size 255 microns, specimen from Crosswise lake near Cobalt, Ontario)

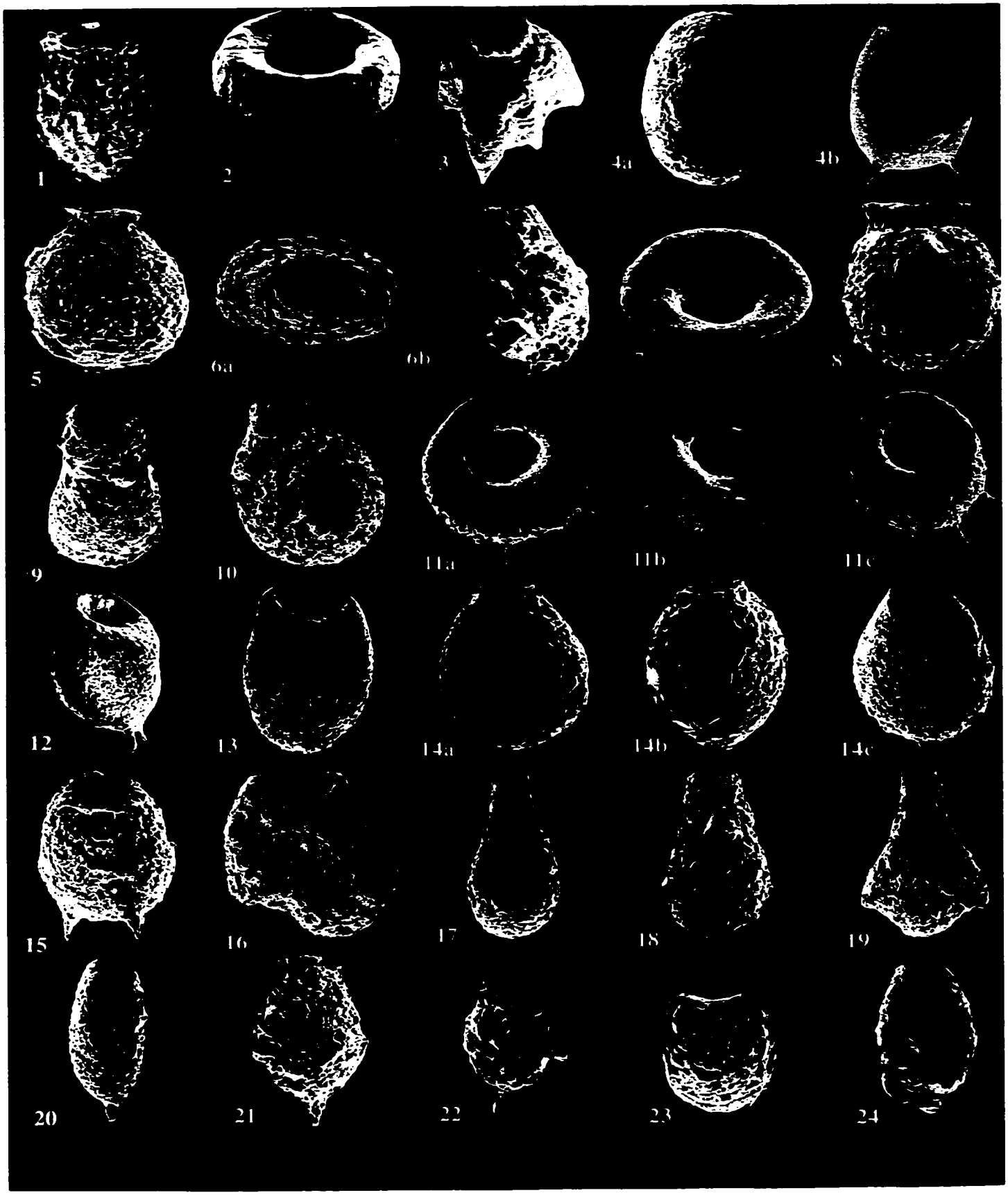
20. *Difflugia protaeiformis* Lamark 1816 strain "acuminata" Reinhardt et al. 1998 (size 98 microns, specimen from Crosswise Lake near Cobalt, Ontario)

21. *Difflugia protaeiformis* Lamark 1816 strain "amphoralis" Reinhardt et al. 1998 (size 75 microns, specimen from Peterson Lake near Cobalt, Ontario)

22. *Difflugia protaeiformis* Lamark 1816 strain "claviformis" Reinhardt et al. 1998 (size 75 microns, specimen from Peterson Lake near Cobalt, Ontario)

23. *Centropyxis constricta* Ehrenberg 1843 strain "aerophila" Reinhardt et al. 1998 (size 142 microns, specimen from Peterson Lake near Cobalt, Ontario)

24. *Difflugia oblonga* Ehrenberg 1832 strain "glans" Reinhardt et al. 1998 (size 146 microns, specimen from Lake Sentani, Irian Jaya, Indonesia)


1
2
3
4a
4b
5
6a
6b
7
8
9
10
11a
11b
11c
12
13
14a
14b
14c
15
16
17
18
19
20
21
22
23
24

CHAPTER 2. Arcellaceans (thecamoebians): New Tools for Monitoring Long and Short Term changes in Lake Bottom Acidity

ABSTRACT

James Lake, northeastern Ontario, Canada, has been impacted by the dumping of waste rock from a pyrite mine. High levels of Fe, Al and SO_4, and low pH (2.0-5.5) are recorded in the lake. Lake configuration and current direction result in contaminated areas being restricted to the southwestern portion of the lake. Near neutral pH and low metal levels are recorded elsewhere. Analysis of arcellacean faunas from the lake indicate that one species, *Arcella vulgaris*, is able to thrive in even the most hostile areas of the lake. The absence of other arcellaceans indicative of contaminated substrates in higher pH lakes, such as centropyxids and *Difflugia protaeiformis* strains, suggests that pH is the dominant control on the distribution of this assemblage. Analysis of arcellaceans from a core at the site indicates that contamination and acidification (pH values < 5.5) problems in James Lake have existed for at least 1300 years, clearly predating mining activity. Prior to that time high proportions of centropyxid species indicate less acid conditions (pH >5.5) prevailed, but a stressed environment existed for several thousand years. The recognition that arcellacean faunas can now be used to characterize industrially and naturally contaminated environments of both low and high pH, provides an important new paleolimnological tool.

INTRODUCTION

Arcellaceans "Thecamoebians" are testate rhizopods, characterized by the presence of lobose pseudopods, an amoeboid sarcodine cell, and a very simple sac-like shell, or test. These organisms occur abundantly in Quaternary to Recent lacustrine sediments (Loeblich and Tappan 1964). Most arcellaceans build their tests by agglutinating foreign particles (xenosomes) in an autogenous cement, usually mucopolysaccharide, forming xenogenous tests. The nature of the xenosomes is entirely controlled by the composition of the substrate, and may consist of sand grains and/or diatom frustules (Medioli and others 1990).

In a series of pilot studies arcellaceans have been successfully used to reconstruct late Quaternary-Holocene lacustrine environments (Scott and Medioli 1983; Patterson and others 1985; Medioli and Scott 1988; McCarthy and others 1995; Ellison 1995) and have proven to be excellent indicators of various, chemically polluted and rehabilitated sub environments within lakes affected by industrial and mining pollution (Asioli and others 1996; Patterson and others 1996; Kumar and Patterson 1997; Reinhardt and others 1998). These studies have shown that there are few benthic environmental indicators in lacustrine environments with the potential for such broad limnological utility as arcellaceans. Their small size (60-300 μm) and generally high abundance mean that statistically significant populations are present even in very small samples. Research has documented within-species "morphing" of the asexually reproducing organisms in response to environmental stresses (Reinhardt and others 1998). Since they reproduce

rapidly (generation times of only a few days), they are excellent ongoing indicators of an ecosystem's health. Conventional biological and chemical environmental proxies can only monitor present conditions in a lacustrine environment. For example, commonly used benthic bioindicators such as ostracodes and mollusks tend to dissolve in the lower pH environments typical of freshwater deposits. Other more resistant bioindicators such as diatoms, pollen, spores, and chrysophytes do not generally reflect conditions at the sediment-water interface (Medioli and Scott 1988). The agglutinated test and organic cement of the arcellaceans are very resistant to dissolution. They are therefore excellent indicators of both short- and long term trends (Patterson and others 1985).

This paper demonstrates a new role for arcellaceans in paleolimnological research, as they can be a cost effective tool for deciphering short and long term lake-bottom acidity levels. The research was carried out in James Lake, located in the environmentally sensitive Temagami region of northern Ontario, and polluted earlier this century by the dumping of sulfide-rich waste rocks from a pyrite mine (Fig. 1). As a baseline the pH controlled distribution of arcellacean fauna throughout the lake was determined to establish arcellacean limnological proxies. To assess long-term changes to the lake, this proxy data was used to interpret paleolimnological conditions as recorded in a short core (Fig. 2).

MATERIALS AND METHODS

A major advantage of working with arcellaceans is the simple and inexpensive methodology required for processing whereby several samples can be processed in less

than an hour without use of chemicals or expensive equipment (Medioli and others 1990, Medioli and Scott 1988; McCarthy and others 1995; Patterson and others 1996; Reinhardt and others 1998).

Fifty-five samples collected over two field seasons were used in this study. Of the forty samples collected in September 1996, twenty-four were lake bottom samples, six were from a mine contaminated pond, and one from a mine trench (Fig. 1). The remaining nine samples were from a short core (1.05 m) collected in the lake adjacent to the waste rock pile. An additional fifteen samples were collected in September 1997, of which eleven were from the lake, three from the pond and one from the mine trench. Sediment-water interface samples were collected using an Eckman box corer. Water depth, sedimentology, pH, water temperature, and other physical characteristics were recorded for each location (Table 1). The exact geographic location of each sample was determined using a Trimble Scout Global Positioning System unit.

A commercial sonar device equipped with bottom hardness indicator was used for sample site selection. Samples were collected from muddy substrates. Winnowed sandy substrates generally have small allochthonous arcellacean communities and rocky substrates are normally barren.

The upper 2-3 mm of sediment from each Eckman grab was removed for micropaleontological analysis (arcellaceans are epifaunal) to isolate arcellacean fauna of the sediment-water interface. The populations found in these samples are representative of conditions at the site for several seasons. In general bioindicators provide a better overall indication of local conditions than the snapshot provided by geochemical methods

as these results often vary markedly with the season, recent precipitation levels, etc. A one cm deep sediment sample was used for geochemical analysis of pore water. We did not analyze bulk sediment samples because the chemical makeup of compounds and elements found in pore water are in forms that can be directly ingested and absorbed by most organisms (Luoma 1983; Campbell 1995). Samples for micropaleontological analysis were first screened with 1000 μm sieve to remove coarse organics, then with a 55 μm screen to retain arcellaceans and to remove silts and clays. To avoid decay, all samples were treated with isopropyl alcohol and refrigerated after collection.

All micropaleontological samples were then subdivided into aliquots for quantitative analysis using a wet splitter (Scott and Hermelin 1993). Wet aliquots were examined under a binocular microscope and, whenever possible, a statistically significant number of arcellaceans were counted (Patterson and Fishbein 1989). All samples collected from the open lake contained large arcellacean populations with the exception of those from "Green Holes". The "Green Holes" are shallow (15-25 cm deep) , almost circular depressions of about 1.0 m diameter at the lake bottom inhabited solely by colonies of green and blue-green algae, because the low pH makes these areas toxic to grazers and other organisms and are found in very shallow waters (1.0-1.5 m water depth) close to the waste rock dump. All samples from the pond and mine trench contained only rare specimens of *Arcella vulgaris*, and are considered barren. Although the total arcellacean counts from the core samples were lower than generally obtained at the surface, counts were sufficiently high to permit direct comparison with surface samples.

JAMES LAKE AND THE NATURE OF THE PROBLEM

James Lake is a mesotrophic, "C" - shaped lake located along Highway 11, 10 km north of Temagami in northeastern Ontario (Fig. 1). The narrow lake covers an area of 45.3 hectares, and is elongated in a north-south direction. An inlet stream at the north end feeds the lake, with an outlet at the south end. A constriction divides the lake into north (80%) and south (20%) basins. The southern basin is shallow and reaches a maximum depth of only 4.0 m. The northern basin is deeper with a maximum depth of 15.0 m (Fig. 1). The northern basin is stratified, with both oxygen levels and temperature dropping significantly beneath 5.0 m depth. During our sampling in early September, 1996 and 1997 the upper epilimnion temperature reached as high as 26.7° C and oxygen levels as high as 9.0 mg/L were recorded. These values dropped to 8.9° C and 2.4 mg/L respectively in the lower hypolimnion (Table 1).

The main rock types surrounding the lake are felsic and mafic volcanic rocks, pillow lavas, granites, granodiorites and gabbros of Keewatin age (3.4 to 2.3 b.y.). The volcanic rocks are rich in pyrite. Pyrite was discovered in lenses within greenschist in 1903. The Northland Pyrite Mine Co. mined pyrite on the southwest shore of the lake from February, 1906 to March, 1911, shipping more than 38,000 tons of pyrite to Cobalt, a nearby silver mining town. Sulfuric acid made from the pyrite was used in the extraction of silver. Most waste rock from this mine was dumped on the southwest lake shore, and in the lake itself (Fig. 1). The waste rock pile (3500 m^3) contains large

amounts of pyrite (about 25%) with lesser amounts of pyrrhotite and traces of chalcopyrite and gold.

In 1979 local residents expressed concern that seepage from the waste rock pile and mine trench was having a detrimental effect on Granite Lake, immediately (about 1.0 km) downstream from James Lake.

An Ontario Ministry of the Environment (MOE) report indicated that iron staining was visible on all rocks cropping out along the shore throughout the entire southern basin (Gale 1990), as we also observed in both 1996 and 1997. The MOE study, began only two days after ice had melted in the lake on May 10, 1989, and continued throughout that summer, reported little evidence of insect benthos near the mine site. Three key water quality parameters (iron, aluminum and sulfate) were found to exceed provincial guidelines.

Because the substrate in the southern basin contains large amounts of iron oxides, the clays and fine sands found there are of a rusty brown color. The bottom sediments in the northern basin of the lake are gray colored organic rich muddy sediment or "gyttja".

The pH of water and bottom sediments of the north basin is neutral (pH 6.8 to 7.0) and is not generally affected by conditions in the south basin because of the north-south water flow in the lake. The pH in the southern basin varies from <2.0 near the waste rock pile. Low pH values near the waste rock pile (pH <5.5) were generated by percolating flow of rain water that oxidizes sulfide from pyrite and pyrrhotite in the waste rocks and bedrock (Gale 1990). There is a gradual increase in pH values to almost neutral (pH 6.8) in more distal areas of the south basin (Table 1).

Sulfide ions from the mineralized waste rocks and hydrogen ions from water react to produce sulfuric acid (H_2SO_4). In areas of the lake very near the waste rock pile, sediment sulfate concentrations are very high, up to 17, 238 mg/L, at station 97-7 (Table 2). However, most pore water sulfate values measured from lake sediments adjacent to the waste rock pile were much less (396 mg/L and 682 mg/L at Stations 97-15 and 97-10 respectively). Sediment pore water sulfate values drop to acceptable levels (9.9-25.2 mg/L) within 100 m of the waste rock pile, although an anomalously high value of 668 mg/L was recorded in the eastern portion of the south basin at station 97-12.

Sulfate is almost always found in drinking water, and often in relatively high concentrations (Moore 1991). Drinking water guidelines are 250 mg/L in the US and 500 mg/L in Canada. The development of guidelines was based on aesthetic factors, particularly bad taste, as human health problems are not associated with these levels. However, high sulfate concentrations cause acidification of surface waters which does have a serious impact on fish and other aquatic species (e.g. fish cannot survive at pH <5.5; Baker and Christensen 1991).

Extensive deposits of $Fe(OH)_3$ and Fe_2O_3, up to 5 cm thick were found covering the bottom of the southern basin. These layers precipitate out when there is a rapid increase in pH of lakewater, which occurs in James Lake during spring freshet (Gale 1990), and can suffocate benthic organisms (Moore 1991). Sediment pore water Fe level varied from 1.52 mg/L in the northern basin to 11,800 mg/L near the waste rock pile (station 97-7; Table 2). Iron concentration in lake water varied from 0.09 mg/L in the northern basin to 2.4 mg/L near the waste rock pile (Gale 1990). All pore water and lake

water samples were found to be well in excess of the provincial drinking water guideline of 0.3 mg/L for iron. The low drinking water guideline/standard is based more on aesthetics than a health concern, as the taste of iron can readily be detected at 1.8 mg/L. Very high Fe concentrations can also lead to staining of laundry and plumbing and massive growth of bacteria in water systems (Moore 1991). The recommended daily intake for men is 10 mg and 18 mg for women. At 0.3 mg/L the daily intake of iron from drinking water would be only 0.6 mg.

Iron is so plentiful in the environment and as an essential trace element that high levels often accumulate in invertebrates with little ill effect (Vymazal 1984; Tessier, and others 1984). However, extremely high concentrations of iron, as found in substrate pore water near the waste rock pile can have toxicological significance (Moore 1991). Many species of insects are affected by Fe concentrations in excess of 16 mg/L. The high Fe pore water concentrations, the $Fe(OH)_3$ and Fe_2O_3 deposits coating substrate throughout the western southern basin, and elevated levels of Fe in the lake water itself may explain the observed low number of insects found there (Gale 1990). Although iron concentration guidelines for the protection for higher aquatic life range from 0.3 mg/L to 1.0 mg/L their tolerance is much greater (>10 mg/L; Moore 1991). During our study and as reported by the MOE (Gale 1990), a large number of vertebrates (fish and amphibians) were observed in the southern basin, although mostly in the eastern part.

Sediment pore water aluminum concentrations varied from 0.19 mg/L to 415 mg/L at station 97-7 (Table 2). Aluminum values in the lake water itself varied from 0.05 mg/L in the northern basin to 0.24 mg/L near the waste rock pile (Gale 1990). Aluminum is not

essential for survival but it is found in virtually all plant and animal species. In higher pH regimes aluminum quickly forms relatively stable complexes (Plankey and Patterson 1987, 1988). However, in lower pH environments (<pH 5.5) such as found in the south basin of James Lake it mobilizes in biologically useable forms (Burrows 1977). Water quality guidelines for aluminum are highly variable and reflect differing opinions on the hazard posed by aluminum in drinking water but 0.2 mg/L seems to be the maximum allowable concentration agreed to by most agencies (Moore 1991). The aluminum concentration guidelines for the protection of aquatic life in Canada and several European nations are 0.005 mg/L at pH<6.5 and 0.1 mg/L at pH >6.5 (Burrows, 1977).

RESULTS AND DISCUSSION

James Lake is an ideal laboratory for assessing the sensitivity of arcellaceans in monitoring industrial pollutants (Kumar and Patterson 1997). The flow of lake water is from north to south, exiting near the source of pollution at the Northland Pyrite Mine Co. site. This circulation pattern has created habitats that range from unimpacted in the northern basin, and in some portions of the southern basin, to extremely contaminated near the mine site itself. This is an useful characteristic, as utilization of any flora or fauna as a bioindicator is comparative. The distribution of organisms in an uncontaminated environment found "upstream" is compared with that of that recorded in the contaminated area. This data can then be used to assess environmental damage "downstream", or in similarly polluted areas.

There is a mature literature concerning the constraints on arcellacean faunas in lake environments of eastern North America. For that reason, and since the thrust of this research is the characterization of arcellacean faunas as bioindicators of contaminated areas, the various faunas from the relatively uncontaminated near neutral pH environments elsewhere in James Lake are not described in detail here. Suffice it to say that these faunal assemblages are controlled by numerous factors including water temperature and level of oxygenation in areas beneath the hypnocline, substrate, and vegetation. The Shannon Diversity Index values for these faunas also tends to be much greater, ranging up to near 2.5 in the northern basin compared to <1 in areas of the southern basin.

Within assemblages certain species are particularly useful as environmental indicators. For example, in James Lake *Arcella vulgaris* varies inversely to most other arcellacean taxa (Fig. 3). High abundance of *Arcella vulgaris* seems to be closely linked to the environments of James Lake with elevated metal concentrations and low pH. *Arcella vulgaris* is the dominant species in the most contaminated areas (<pH 5.5), but forms < 5 % of the total assemblage (or even totally absent) in normal pH regions (6.5-7.5; Fig. 4). *Arcella vulgaris* is an important component of arcellacean faunas in boggy ponds in the Arctic and further south (Collins and others 1990). The low pH typical of these ponds has preadapted this species to dominate similar low pH environments. The most acidic sites in the lake with pH < 2.0 were in "Green Holes" near the waste rock pile. Few specimens of *Arcella vulgaris* were even found in this environment.

Other opportunistic taxa notably missing from the low pH environments (pH<5.5) of James Lake include the centropyxids. Many lakes in the vicinity of the nearby town of Cobalt are heavily contaminated by heavy metals and other mining related contaminates, but were deposited under alkaline conditions. In higher pH environments in the Cobalt area centropyxid species such as *Centropyxis aculeata* often dominate heavy metal contaminated substrates (Patterson and others 1996, Reinhardt and others 1998). Also notably missing from the lower pH environments of this lake are any strains of *Difflugia protaeiformis*. This species is commonly abundant in portions of James Lake with pH of 6.5-7.5, and also in higher pH and highly contaminated areas of Peterson and Crosswise lakes (Reinhardt and others 1998).

In Lake Orta of northern Italy the 'rapa' strain of *Difflugia protaeiformis* was reported as being very abundant in an industrially polluted low pH (3.9-4.5) settings (Asioli and others 1996). It is apparent that *Difflugia protaeiformis* occurs in environments ranging from low pH to polluted high pH (6-7.5). The association of *Difflugia protaeiformis* with low pH environments require further study. The absence of other opportunistic, contaminated substrate indicator species leads us to conclude that pH may be a greater limiting factor than either high Fe or Al in controlling the presence or absence of the *Arcella vulgaris* dominated fauna in James Lake. The recognition that Arcellacean faunas can be used to distinguish both low and high pH, heavy metal contaminated environments, is significant as this means that deployment of the group as a paleolimnological indicator in most lacustrine settings is now possible.

PALEOLIMNOLOLOGICAL ANALYSIS

A major impetus for research in the James Lake area was concern by local area residents mainly cottagers and wilderness outfitters that ongoing contamination from the site was having an adverse effect. Although it is obvious that mining activity has had an impact on the lake there are several requirements that must be met before an effective ecosystem management for James Lake, or any other body of water under study, can be achieved. These requirements include knowledge of baseline conditions and natural variability, identification of the time when conditions in the lake first began to change, and a description of possible outcomes of such changes (Ford 1988). These requirements include a temporal component and thus require long-term data so that realistic targets for remediation efforts can be set, anthropogenic activity discerned and measured, and future scenarios evaluated (Likens 1988; Elliot 1990; Smol 1992). Aquatic ecosystem managers generally choose from four main sources of data to address these objectives. These data include direct historical measurements, space-for-time substitution (i.e. comparing chemistry and biota in similar but unaffected lakes), computer models based on empirical or dynamic data, and paleolimnological constructions (Smol 1992).

The unusual configuration of the lake and position of the pollution source near the outlet permitted a comparative approach within the lake itself, a scenario not usually possible in most small lakes. The geochemical data (Mason 1998) and the observed arcellacean fauna indicated a highly contaminated area adjacent to the old mine site suggesting that mining activity has seriously impacted the lake. However, according to

the requirements for effective aquatic management a determination of baseline conditions in the southern basin of the lake must be made prior to attempting any remedial action.

As in most lakes, direct historical measurements are not available for the time-frame of interest in James Lake. Thus paleolimnological methods are the best approach for determining these baseline conditions. Unfortunately, except where the sediment sink is large and stable, geochemical methods do not always provide an accurate depiction of the historical record (Horowitz 1991; Bethke 1996) due to mobilization and redistribution of metals and other constituents in the substrate. On the other hand skeletonized microfossils, except in areas of excessive bioturbation, do not migrate and archive data on the scale of millennia to seasons, providing very valuable information to ecosystem managers. Benthic micropaleontological bioindicators such as arcellaceans, with their very high preservation potential, are thus amongst the best tools to make a temporal assessment of the history of pollution and/or remediation of the contaminated area.

The upper 30 cm of a piston core (JLC-96-1) collected in the lake adjacent to the waste rock pile is characterized by *Arcella vulgaris* dominated assemblages (Figs. 1, 2). As indicated by the distribution of this species in surface sediments the depositional environment through this interval was under low pH (<5.5) and possibly highly contaminated conditions. Lower intervals of the core with statistically significant populations are dominated by various centropyxid species and indicate environmentally stressed but higher pH conditions. This is caused by gradual and mild acidification in this part of the lake due to weathering of pyrite rich rocks much before pyrite mining began in

the region. Centropyxid species are capable of withstanding a variety of hostile conditions better than most other arcellacean species, including cold temperature (Delcoitre 1956), low salinity conditions (< 5‰; Decloitre 1953; Scott and Medioli 1980; Patterson and others 1985; Honig and Scott 1987), low nutrient conditions, oligotrophic conditions (Schönborn 1984), and sites heavily contaminated by mercury and arsenic (Patterson and others 1996). The high abundances of the seasonally planktic arcellacean *Cucurbitella tricuspis* (Schönborn 1984) in most samples is the result of current transport unrelated to substrate conditions at the core site. Prior to obtaining ^{14}C dates from a nearby core collected in 1997 it was assumed that the rise of the *Arcella vulgaris* dominated fauna coincided with the initiation of mining activity and lake acidification. As the average sedimentation rates in lakes varies between 1 and 5 mm per year (Förster and Wittmann 1981) we assumed that the interval dominated by *Arcella vulgaris* had been deposited since mine activity began. However, five ^{14}C dates have been obtained from three newly obtained shallow cores in September 1997 very close to the core site JLC-96-1 (Table-3). One of them JLC-97-3 was collected only one meter away from the one studied here. The dates require that sedimentation rate in the area of the lake adjacent to the mine site has been quite low for at least the past 8700 years (Table 3; Fig. 2). Apparently the *Arcella vulgaris* dominated fauna has characterized this site for over 1300 years indicating once again that lake acidification predated mining. Prior to that, centropyxids lived in a higher pH but still stressed environment for several thousand years. Although not always reliable, geochemical analysis of samples from core JLC-97-3

provide corroborative evidence that elevated levels of Fe, Al, and sulfate have also existed for thousands of years at this site (Mason 1998).

The lake in this area also seems to be directly acidified from migration of fluids along natural faults and fractures. A series of "Green Holes", interconnected by narrow linear growths of bright green algae demarcate subsurface fractures. The extremely low measured pH values of 2.0 marked by the algal growths suggests that highly acidic springs are entering the lake here. Before obtaining ^{14}C dates we hypothesized that the acidic waters venting from the Green Holes was leachate from the waste pits that being focused by the natural fracture system. However, large veins of pyrite-rich ore were naturally exposed on the shore in the western part of the southern basin prior to the establishment of a pyrite mine (Gale 1990). The dates make it clear that natural acidification of the site, from sulfides leaching from these naturally exposed large pyrite veins, and from subsurface springs, began long before any anthropogenic contribution. This occurrence is not unusual as any area characterized by surficial metal-bearing formations will have elevated metal values (see Förstner and Wittmann 1981, for examples). In fact, detection of these elevated levels is a major exploration tool used by mineral exploration companies. Although mining activity at James Lake has at least locally exacerbated the contamination and acidification problem in the lake it must also be recognized that the lake is naturally polluted. Similar results have been recorded in lakes of the Adirondack region of New York State. In this area recent acid precipitation has contributed to lake acidification but substantial declines in pH had occurred thousands of years previously (Whitehead and others 1989).

Environmental managers have thus far concentrated their James Lake remediation efforts on increasing the pH of lake water in the western portion of the southern basin through construction of limestone barriers. These measures have proven ineffectual thus far. Remediation goals should therefore be revised, unless the goal of remediation here is to create an environment unrelated to natural conditions.

ACKNOWLEDGMENTS

NSERC Research Grant OGP0041665 to RTP and a Cushman Foundation for Foraminiferal Research grant to AK supported this research. We gratefully acknowledge the assistance of the students in the department of Earth Sciences Environmental Geology Field Camp (67.285) for their help in the field and H. E. Anderson for critical comments on the manuscript.

REFERENCES

Asioli A, Medioli FS, and Patterson RT (1996) Thecamoebians as a tool for reconstruction of paleoenvironments in some Italian lakes in the foothills of the southern Alps (Orta, Varese and Candia). J Foraminiferal Res 26: 248-263

Baker JP and Christensen SW (1991) Effects of acidification on biological communities in aquatic ecosystems. In: Charles D F (Ed) Acidic Deposition and Aquatic Ecosystems: Regional Case Studies. Springer-Verlag, New York, NY, p. 83-106.

Bethke CM (1996) Geochemical Reaction Modelling. Oxford University Press, Inc. New York, NY, 397 p

Burrows WD (1977) Aquatic aluminum: chemistry, toxicology and environmental prevalence. CRC Crit Rev Environ Control 7:167-216

Campbell PGC (1995) Interactions between trace metals and aquatic organisms: a critique of the free-ion activity model. In: Tessier A and Turner DR (eds) Metal Speciation and Bioavailability in Aquatic Systems. John Wiley & Sons Ltd., N. Y.

Collins ES, McCarthy FM, Medioli FS, Scott DB and Honig CA (1990) Biogeographic distribution of modern thecamoebians in a transact along the eastern North American coast. In: Hemleben C, Kaminski MA, Kuhnt, W and Scott DB, (eds), Paleoecology, Biostratigraphy, Paleoceanography and Taxonomy of Agglutinated Foraminifera. NATO Adv Study Inst Ser C, 327:783-791

Decloitre, L (1953) Recherches sur les Rhizopodes thecamoebiens d' A. O. F. (Suite). Faune du Lac Tamna (Senegal). Bull. De l'Institut Francais d'Afrique Noire, 31, p. 249.

Deltapoint (1996) Deltagraph User's Guide. Monterey, CA

Elliot JM (1990) The need for long-term investigation in ecology and the contributions of the Freshwater Biological Association. Freshw Biol 23:1-5

Ellison RL (1995) Paleolimnological analysis of Ullswater using testate amoebae. J Paleolimnol 13: 51-63

Ford J (1988) The effects of chemical stress on aquatic species composition and community structure. In: Lewin S A, Harwell M A, Kelly J R and Kimball K D (eds), Ecotoxicology: problems and approaches, Springer-Verlag, New York, p 99-144

Förstner O and Wittmann GTW (1981) Heavy metals in industrial and domestic effluents, Chapter G2. In: Metal Pollution in the Aquatic Environment. Springer-Verlag, Heidelberg, Germany, pp. 340-359

Gale P (1990) James Lake, Northland Pyrite Mine. Ont Dept Environ Techn Memo. Sudbury, 15 p

Honig CA and Scott DB (1987) Post glacial stratigraphy and sea-level change in southwestern New Brunswick. Canadian Journal of Earth Sciences, 24: 354-364.

Horowitz AJ (1991) A primer on sediment-trace element chemistry, 2nd rev. ed. Lewis Publishers, Inc., Chelsea, Michigan, 136 p

Kukal Z (1971) Geology of recent sediments. Academic Press Inc., London, 490 p

Kumar A and Patterson RT (1997) Arcellaceans (Thecamoebians) as proxies of lake bottom acidity: an example from James Lake, northeastern Ontario. Geol Assoc Canada/ Mineral Assoc Canada Annu Meet, May 19-21 (Abstract), p. A-150

Likens GE (Ed) (1988) Long term studies in ecology: Approaches and alternatives. Springer-Verlag, New York. 214 p

Loeblich AR Jr, Tappan H (1964) Sarcodina, chiefly "Thecamoebians" and Foraminiferida. In: Moore R C (Ed), Treatise on Invertebrate Paleontology, Part C. Protista II, 1, Geol S Am & U Kan Press, pp. C 16-C 64

Luoma SN (1983) Bioavailability of trace metals to aquatic organisms – a review. Sci. Total. Environ, 28:1-22

Mason G (1998) A study of the effects of past mining activities on James Lake sediment Chemistry, Carleton University College of Natural Sciences Environmental Science Institute, Unpublished Honours Thesis, 53 p

McCarthy FG, Collins ES, McAndrews JH, Kerr HA, Scott DB and Medioli FS (1995) A comparison of post glacial Arcellacean ("Thecamoebian") and pollen succession in

Atlantic Canada, illustrating the potential of arcellaceans for paleoclimatic reconstruction. J Paleont 69:980-993.

Medioli FS and Scott DB (1988) Lacustrine thecamoebians (mainly Arcellaceans) as potential tools for paleolimnological interpretations. Paloeogeogr, Paloeoclimatol, Paloeoecol, 62:361-386

Medioli FS, Scott DB, Collins ES and McCarthy FMG (1990) Fossil thecamoebians: present status and prospects for the future. In: Hemleben C, Kaminski M A, Kuhnt W. and Scott DB (eds) Paleoecology, Biostratigraphy, Paleoceanography and Taxonomy of agglutinated Foraminifera. NATO Adv Study Inst Ser C, 327:813-840

Moore JW (1991) Inorganic contaminants of surface water: research and monitoring priorities. Springer-Verlag N. Y. , 334p

Patterson RT, MacKinnon KD, Scott DB and Medioli FS (1985) Arcellaceans (Thecamoebians) in small lakes of New Brunswick and Nova Scotia: modern distribution and Holocene stratigraphic changes. J Foraminiferal Res 15: 14-137

Patterson RT and Fishbein E (1989) Re-examination of the statistical methods used to determine the number of point counts needed for micropaleontological quantitative research. J Paleont 62:245-248

Patterson RT, Barker T and Burbridge SM (1996) Arcellaceans (Thecamoebians)as proxies of arsenic and mercury contamination in northeastern Ontario lakes. J Foraminiferal Res 26:172-183

Plankey BJ, Patterson HH (1987) Kinetics of aluminum fulvic acid complexation in acidic waters. Env Sci Tech, 21:595-601

Plankey BJ, Patterson HH (1988) Effect of fulvic acid on the kinetics of aluminum fluoride complexation in acidic waters. Env Sci Tech 22:1454-1459

Reinhardt ED, Dalby A, Kumar A , and Patterson RT (1998) Utility of arcellacean morphotypic variants as pollution indicators in mine tailing contaminated lakes near Cobalt, Ontario, Canada. Micropaleont 44 (2): 131-148

Schönborn WS (1984) Studies on remains of Testacea in cores of the Great Woryty Lake (NE-Poland). Limnologica (Berlin), 16:185-190

Scott, DB and Medioli FS (1980) Post glacial emergence curves in the maritimes determined from marine sediments in raised basins. Proceedings of coastlines '80. National Science and Engineering Research Council, pp. 428-449.

Scott DB and Medioli FS (1983) Testate rhizopods in Lake Erie: modern distribution and stratigraphic implications. J Paleont 57: 809-820

Scott DB and Hermelin JOR (1993) A device for precision splitting of micropaleontological samples in liquid suspension. J Paleont 67: 151-154

Smol, JP (1992) Paleolimnology: an important tool for effective ecosystem management. J Aquat Ecosyst Health 1:49-58

Tessier A, Campbell PGC, Auclair JC, and Bisson M (1984) Relationships between the partitioning of trace metals in sediments and their accumulation in the tissues of the freshwater mollusk Elliptio complanata in a mining area. Can J Fish Aquat Sci 41:1463-1472

Vymazal J (1984) Short-term uptake of heavy metals by periphyton algae. Hydrobiologia 119:171-179

Whitehead DR, Charles DF, Jackson JP, Smol JP, Engstron DRJ (1989) The developmental history of Adirondack (N.Y.) lakes. Paleolimnol 2:185-206

Figures In Text

Figure 1. Location Map showing position of James Lake in northeastern Ontario. Bathymetric map of lake shows relative position of sample and core stations as well as general layout of abandoned Northland Pyrite Mine Co. site.

Figure 2. Sedimentology, biostratigraphy and 14C dates from a core collected in James Lake adjacent to the waste rock pile. 14C date was obtained from a nearby core collected for geochemical analysis (Mason 1998).

Figure 3. Scatter plot of relative distribution of *Arcella vulgaris* and *Difflugia oblonga* in James Lake samples. The almost exclusive distribution of these species demonstrates the clear affinity that various taxa have for distinctive habitats.

Figure 4. Relative proportion of various taxa, and Shannon Diversity Index in relation to pH in James Lake. The linear least squares method was used to determine the best fit for the linear curve fits using Deltagraph 4.0 (Deltapoint 1996).

Figure 1. Location map of James Lake

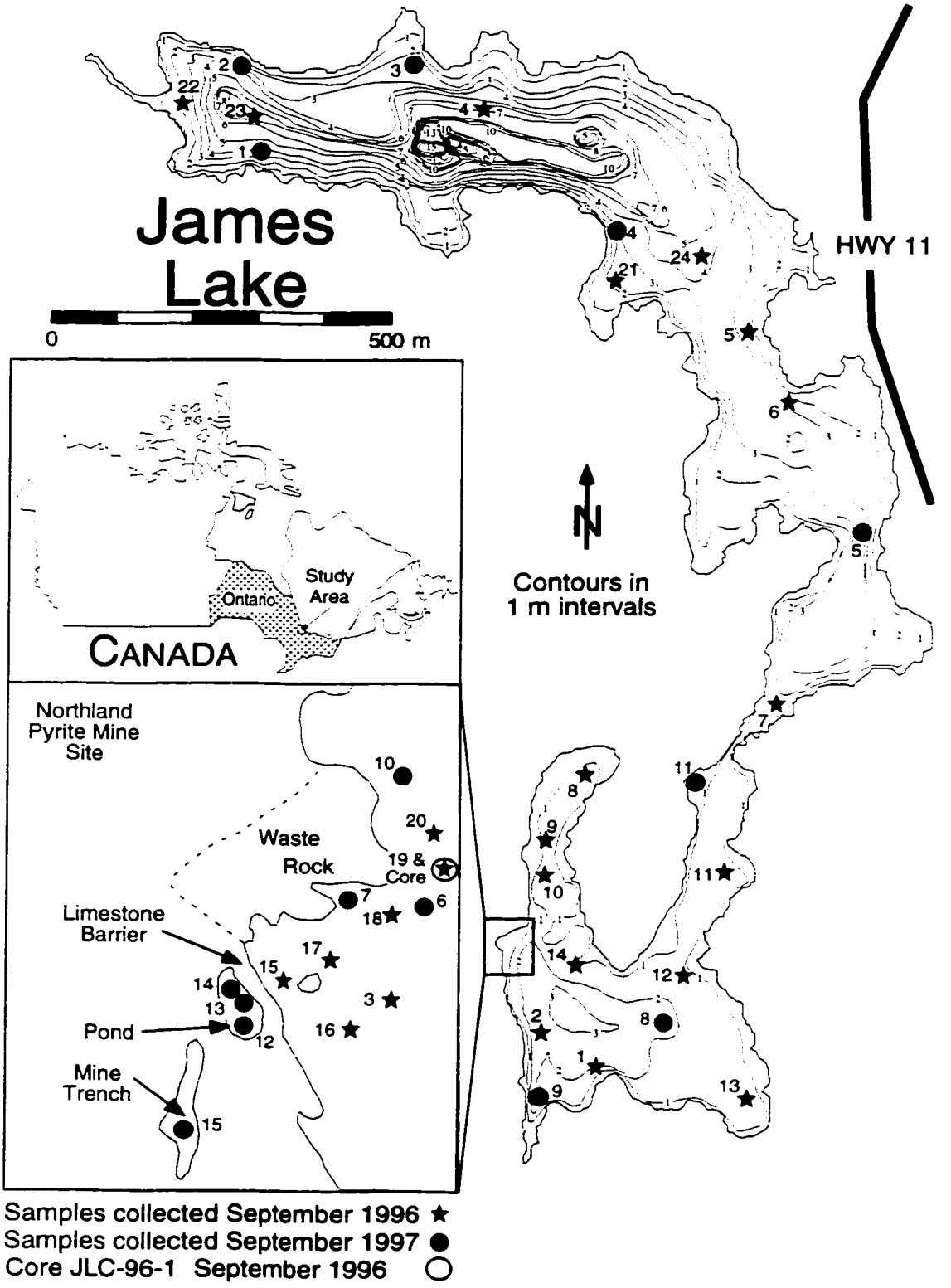


Figure 2

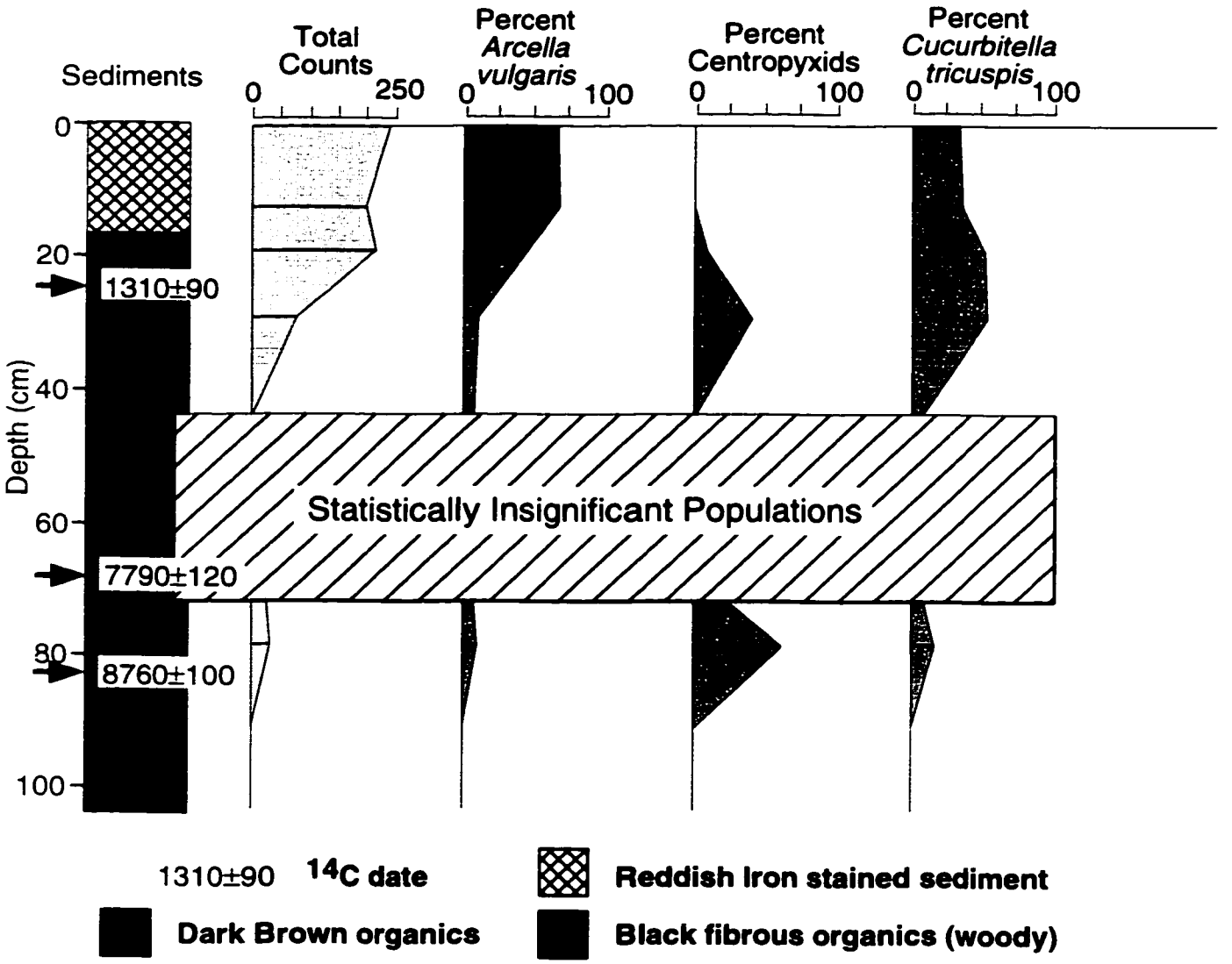

Sediments
Total Counts
0
250
Percent *Arcella vulgaris*
0
100
Percent Centropyxids
0
100
Percent *Cucurbitella tricuspis*
0
100
Depth (cm)
0
20
40
60
80
100
1310±90
7790±120
8760±100
Statistically Insignificant Populations
1310±90 ^{14}C date
Reddish Iron stained sediment
Dark Brown organics
Black fibrous organics (woody)

Figure 3

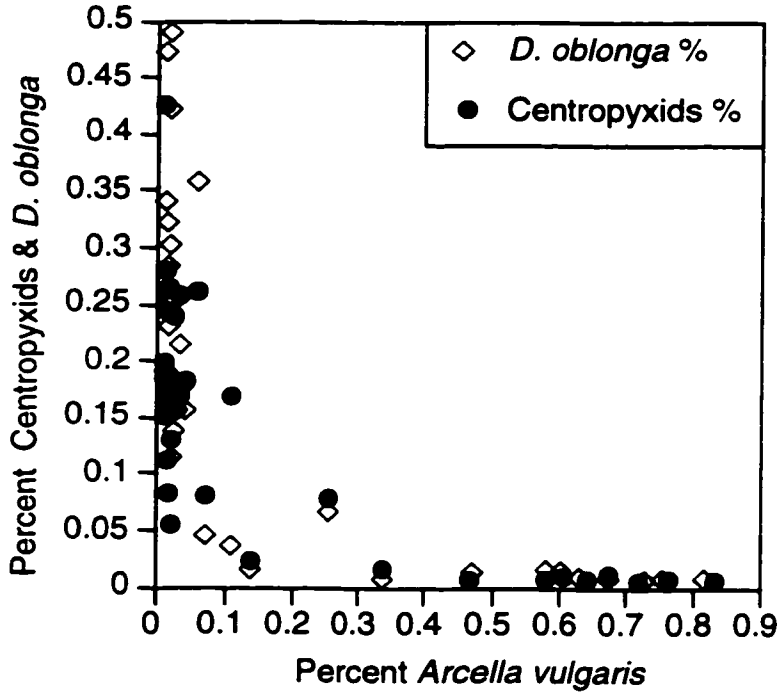

D. oblonga %
Centropyxids %
Percent Centropyxids & D. oblonga
Percent Arcella vulgaris
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9

Figure 4

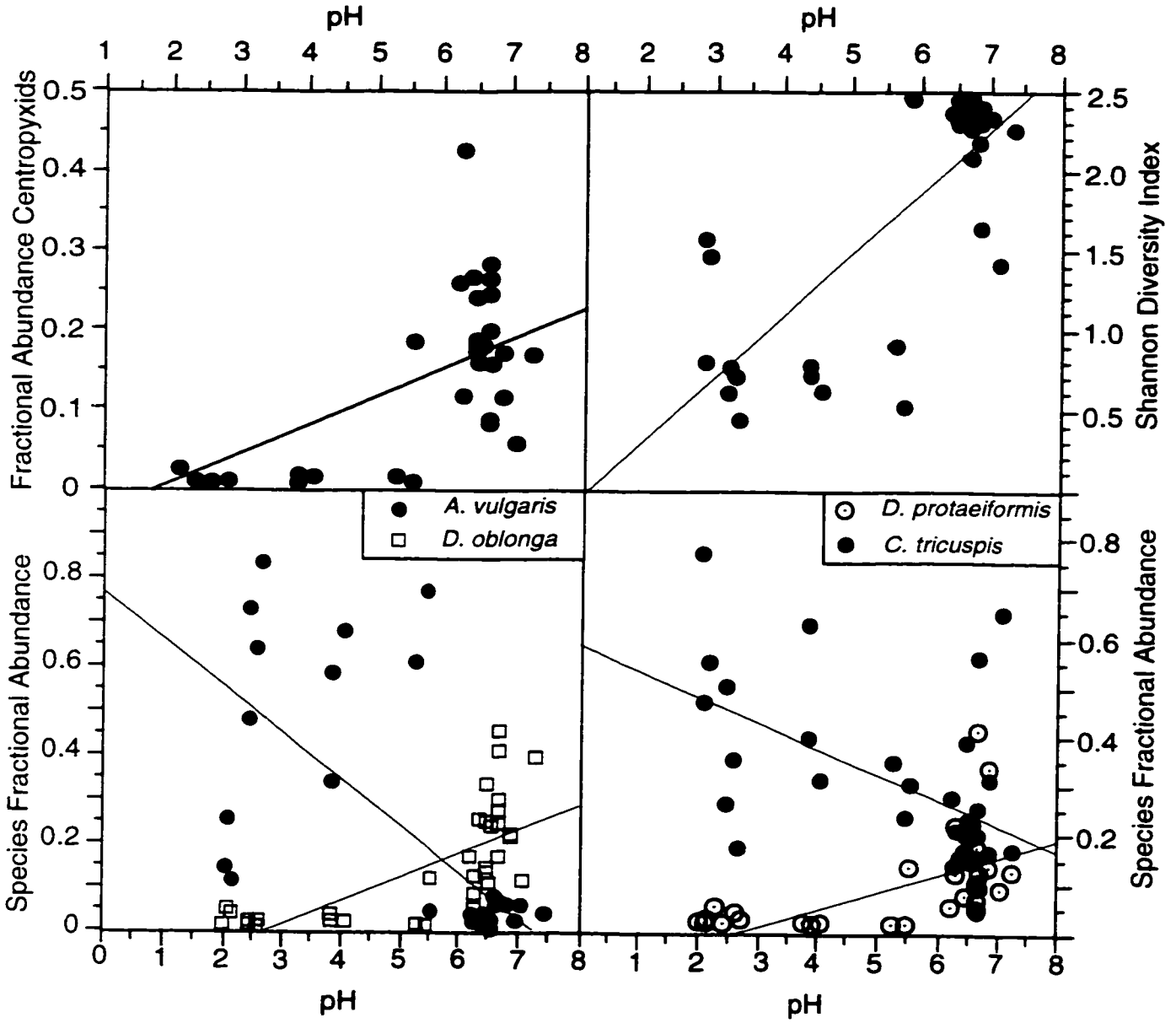

pH
pH
Fractional Abundance Centropyxids
Shannon Diversity Index
A. vulgaris
D. oblonga
D. protaeiformis
C. tricuspis
Species Fractional Abundance
Species Fractional Abundance
pH
pH

Table 1. Parameters measured at each sample station; water depth, oxygen concentration, pH, sediment color, and sediment texture. Sample station location shown in Figure 1.

Sample Station	Water Depth (m)	Sed./Water Interface pH	Surface Water pH	Sed./Water Interface O_2 (mg/L)	Surface Water O_2 (mg/L)	Surface Water Temp.(C)	Sed./Water Interface Temp.(C)	Sediment Texture	Sediment Color
JL-96-1	1.8	6.7	7.4	8.2	8.2	23.3	20.7	Clay	Greenish Brown
JL-96-2	2.6	3.9	6.7	5.6	8	22.4	20.4	Clay	Grayish Brown
JL-96-3	0.9	3.9	7.6	6.9	7.6	23.3	21	Clay	Rusty Brown
JL-96-4	9.8	7.1	7.8	1.4	8.3	24.4	6.7	Silt/Clay	Dk. Olive Green
JL-96-5	4.2	6.9	7.2	7.5	8.2	23.8	20.3	Clay	Dk. Olive Green
JL-96-6	2.4	7.3	7.4	7.4	7.6	24.8	20.8	Clay	Dk. Olive Green
JL-96-7	1	6.5	7.6	7.1	8	24.8	20.8	Silt/Clay	Dk. Olive Green
JL-96-8	1.8	6.9	7.1	6	7.1	21.7	21.3	Clay	Dk. Brown
JL-96-9	1.4	6.5	6.5	7.3	7.4	21.8	21.4	Silt/Clay	Grayish Brown
JL-96-10	0.6	2.5	5.7	7.4	8.4	21.7	21.5	Sand/Clay	Light Brown
JL-96-11	1.4	6.5	6.5	7.2	7.3	22.5	21.5	Silt/Clay	Greenish Black
JL-96-12	0.9	6.6	6.8	7.4	7.5	22.5	22.3	Sand/Clay	Dk. Brown
JL-96-13	1.1	6.7	6.8	7.4	7.7	22.3	21.5	Sand/Clay	Greenish Black
JL-96-14	1.1	6.7	6.9	7.4	7.5	22.8	22.5	Clay	Brownish Black
JL-96-15	1.3	2.6	6.9	6.9	7.3	24.6	22.9	Silt/Clay	Lt. Brown
JL-96-16	0.8	2.1	5.5	6.1	7.1	25.4	23.4	Sand/Clay	Brown
JL-96-17	1	4.1	5.7	7.4	8.1	23.4	23.4	Silt	Yellowish Brown
JL-96-18	0.8	5.3	5.9	6.9	6.9	24.7	23.7	Sand/Clay	Dk. Brown
JL-96-19	1.3	5.5	5.9	5.9	7.2	24.3	23.9	Clay	Greenish Black
JL-96-20	0.7	2.2	3.7	5.2	6.8	26.7	25	Clay	Greenish Black
JL-96-21	1	6.4	6.7	6.8	7.7	23.6	22.7	Clay	Greenish Black
JL-96-22	3	6.7	7.1	7.3	7.8	23.6	20.7	Clay	Black
JL-96-23	14.1	6.7	7.1	5.2	7.5	24	8.9	Clay	Black
JL-96-24	5.5	6.7	7.1	7.2	7.3	23.8	19	Clay	Black
JL 97-1	7.8	6.7	7.9	2.4	9	17	13	Clay	Dk. Brown
JL 97-2	3	7	7.3	NA	NA	17.5	17.5	Clay	Dk. Brown
JL 97-3	3.9	7.3	7.3	8.1	8.2	17.8	17.1	Silt/Clay	Greenish Brown
JL 97-4	3.1	7.3	7.3	8.1	8.2	18.2	17.7	Fine Sand	Grayish Brown
JL 97-5	3.5	6.6	7.3	8.6	8.3	18.1	17.1	Fine Sand	Grayish Brown
JL 97-6	1.4	5.7	5.9	8.8	8.8	16.8	16.8	Clay	Rusty Brown
JL 97-7	0.7	4.3	5.9	8.4	8.7	17.3	17.1	Clay	Greenish Brown
JL 97-8	1.4	6.6	6.5	8.1	8.2	17.2	17	Clay	Dk. Green
JL 97-9	1.6	6.1	6.5	8.2	8.1	17.3	NA	Clay	Grayish Black
JL 97-10	1.1	4.4	6	7.9	8	17.9	NA	Clay/Pebbles	Grayish Brown
JL 97-11	1.5	6.4	6.7	8	8.1	18.8	18	Silt/Clay	Brownish Black
JL 97-12	0.3	2.9	2.9	NA	NA	17	17	Silt/Clay	Rusty Brown
JL 97-13	0.3	2.8	2.9	NA	NA	17	17	Silt/Clay	Rusty Brown
JL 97-14	0.3	2.8	2.9	NA	NA	17	17	Silt/Clay	Rusty Brown
JL 97-15	16.7	4	3	2.4	6.7	15.5	NA	Silt/Clay	Rusty Brown

Table 2. Pore-water pH and geochemistry values for Fe, Al, and sulfate at selected stations.

Sample	pH	Al (mg/L)	Fe (mg/L)	Sulfate (mg/L)
JL 97-2	6.73	0.46	2.44	7.5
JL 97-3	6.51	0.38	2.84	7.5
JL 97-4	6.55	0.37	2.36	9.2
JL 97-5	6.33	0.19	1.52	12.4
JL 97-6	2.49	64	1240	2884
JL 97-7	2.12	415	11800	17238
JL 97-8	6.24	1.11	59.7	9.9
JL 97-9	5.56	0.94	64.9	25.2
JL 97-10	2.69	146	6200	682
JL 97-11	6.31	0.43	14.3	18.8
JL 97-12	2.07	155.5	4190	668
JL 97-15	3.46	1.13	32.4	396

Table 3. Radiocarbon dates obtained from wood extracted from cores JLC-97-2, JLC-97-3, and JLC-97-4.

Sample	Laboratory Number	Wat Number	Dated Material	^{13}C	Percent Modern	^{14}C Date
JLC-97-2; 155-157 cm	86860	4045	Wood	-29.37	41.59±0.7	7050±140
JLC-97-3; 24-25 cm	86861	4028	Wood	-24.42	84.97±1.0	1310±90
JLC-97-3; 66-67 cm	86862	4029	Wood	-27.46	37.95±0.5	7790±120
JLC-97-3; 80-81 cm	86863	4030	Wood	-29.39	33.62±0.4	8760±100
JLC-97-4; 46-48 cm	86866	4031	Wood	-24.29	77.09±1.0	2029±100

CHAPTER 3. Assessment of Arcellacean (Thecamoebian) Assemblages, Species, and Strains as Contaminant Indicators in Variably Contaminated James Lake, North Eastern Ontario

ABSTRACT

Conditions in James Lake vary from uncontaminated and near neutral pH conditions through most of the lake, to extremely low pH (2.1 in places) and contaminated with Fe Al and SO_4 adjacent to an abandoned pyrite mine site near the lake outlet. Six assemblages representative of distinct arcellacean habitats were recognized in sediment-water interface samples collected in the lake using Q-mode Cluster Analysis. R-Mode analysis of this distributional data corroborates previous results indicating that arcellacean strains from within the same species are useful for discriminating environments.

The seasonally planktic and thus readily transported *Cucurbitella tricuspis* dominates most samples and had to be deleted from analysis to determine benthic faunal relationships. This species should not be considered in intralake studies. *Arcella vulgaris* overwhelmingly dominates extremely hostile low pH environments (<5.5) near the old mine site in samples where Shannon Diversity Index values of <1.000 are recorded. The highly variable pH in James Lake permitted the determination of precise boundary conditions for distribution of this species. These results indicate that while *Difflugia protaeiformis* "claviformis" is an ideal indicator of industrial contamination under higher pH conditions the *D. protaeiformis* "amphoralis" and "acuminata" strains are more closely linked to uncontaminated muddy substrates characterized by high proportions of

diatoms, a probable important food source. Presence of *Lesquereusia spiralis* seems to be partially linked to substrate with greater numbers typically found in coarser substrates.

INTRODUCTION

The ultility of arcellaceans (thecamoebians) as sensitive paleoenvironmental indicators has been widely demonstrated (Medioli and Scott, 1988; Patterson et al., 1996; Reinhardt et al., 1998). Particularly significant have been studies in Canada and Italy that have linked various arcellacean faunas and pollution levels (see Patterson and Kumar, in press for summary). These studies have shown that various arcellacean species are differentially affected by industrial pollutants. In addition there is a tendency toward within-species "morphing" of these asexually reproducing organisms in response to environmental stresses (Reinhardt et al., 1998; see Kumar and Dalby, 1998, for a completely illustrated guide). Since they reproduce rapidly (generation times of only a few days), they are excellent ongoing indicators of an ecosystem's health. Since their agglutinated tests preserve well they can also be used to recognize long-term temporal variation in environmental parameters.

James Lake in northeastern Ontario, Canada, has been impacted by the dumping of waste rock from a pyrite mine (Figure 1). Adjacent to mine site high levels of Fe, Al and SO_4, and low pH (2.0-5.5) are recorded. Near neutral pH and low metal levels are recorded elsewhere. Kumar and Patterson (in press) have previously determined that one species, *Arcella vulgaris*, is able to thrive in even the most hostile areas of the lake. The absence of other arcellaceans indicative of contaminated substrates in higher pH lakes, such as centropyxids and *Difflugia protaeiformis* strains, suggests that pH is the dominant control on faunal distribution adjacent to the mine site, although analysis of arcellaceans from a core at the site indicates that contamination and acidification (pH values < 5.5)

problems in this part of James Lake have existed for at least 1300 years, clearly predating mining activity (Kumar and Patterson, in press).

The configuration and prevailing current direction in the lake result in contaminated areas being restricted to the southwestern portion of the lake. In this paper we document the distribution of arcellacean assemblages in this ideal natural laboratory as conditions grade from near neutral pH and uncontaminated conditions in the north to extremely contaminated and low pH environments in the south. These results will permit a more precise determination of the boundary conditions constraining the distribution of arcellacean assemblages as well as individual species and strains.

MATERIALS AND METHODS

Field and Laboratory

Thirty-five samples collected over two field seasons were used in this study. Twenty-four samples were collected from James Lake in September, 1996 and eleven additional samples were collected in September, 1997 (Figure 1). Sediment-water interface samples were collected using an Eckman box corer. Fractional abundance of each species, water depth, sedimentology, pH, water temperature, and other physical characteristics were recorded for each location (Table 1). The exact geographic location of each sample was determined using a Trimble Scout Global Positioning System unit and corroborated by triangulating with landmarks on the shoreline.

A commercial sonar device (fish finder) equipped with bottom hardness indicator was used for sample site selection. Where possible, samples were collected from muddy

substrates as winnowed sandy substrates generally have small allochthonous arcellacean communities and rocky substrates are normally barren.

The upper few mm of sediment from each Eckman grab were removed to isolate the epifaunal arcellacean fauna inhabiting the sediment-water interface. Samples for micropaleontological analysis were first screened with a 1000μm sieve to remove coarse organics, then with a 55μm screen to retain arcellaceans and to remove silts and clays. All samples were treated with isopropyl alcohol and refrigerated after collection to avoid decay. Samples were subdivided into aliquots for quantitative analysis using a wet splitter (Scott and Hermelin, 1993). Wet aliquots were examined under a binocular microscope and, whenever possible, a statistically significant number of arcellaceans were counted (Patterson and Fishbein, 1989).

A one cm deep sediment sample was collected in ten of the samples collected in 1997 and used for geochemical analysis of pore water (Table 2). The chemical makeup of compounds and elements found in pore water are in forms that can be directly ingested and absorbed by most organisms and are thus provide results that can be more directly compared to the observed fauna than those obtained from bulk geochemical analyses (Luoma, 1983; Campbell, 1995).

QUANTITATIVE ANALYTICAL PROCEDURES

The nineteen observed arcellacean species and strain data (Table 1) was converted into fractional abundances, and standard errors were calculated according to the formula proposed by Patterson and Fishbein (1989):

$$S_{X_i} = [X_i(1 - X_i)/N]^{1/2}$$

where S_{X_i} is the standard error; X_i is the estimated fractional abundance for each i = 1, 2, 3, ..., I species, where I = the total number of species in the sample; i is each species; and N is the total number of specimens counted in a sample. When making N counts, the actual fractional abundance f_i lies between,

$$X_i - 1.96S_{X_i} \leq f_i \leq X_i + 1.96S_{X_i}$$

95% of the time. Therefore, the 95% confidence interval on the estimated fractional abundances is $X_i + 1.96S_{X_i}$. The standard error for samples having no specimens of a particular species was calculated using the standard error equation ((S_{X_i}); see Mosteller et al., 1970):

$$S_{X_i} = 1 - (0.051/N)$$

All samples contained statistically significant numbers of arcellaceans (Tables 1; see Patterson and Fishbein, 1989, for background on estimating statistical significance). Statistically significant taxa were subjectively determined to be those with abundances equal to the standard error ±1% at the 95% confidence level in at least one sample. Only one arcellacean strain *Centropyxis constricta* 'spinosa' was present in statistically insignificant numbers and was therefore not utilized in cluster analysis. Q-mode cluster

analysis was carried out on arcellacean data in order to group samples with similar species distributions. Samples grouped in this fashion are considered to be representative of a particular environment or biofacies.

Q-mode clustering of the reduced data sets was done on an Apple Macintosh computer using the SPSS v.5.2 statistical software package and Ward's minimum variance method. The results of the cluster analysis were reported as Euclidean distances and arranged in hierarchical dendrograms (Figures 2, 3). The dendrograms were used to define sample and faunal associations. This methodology simulates a statistically based Error-Weighted Maximum Likelihood (EWML) clustering method fully described by Fishbein and Patterson (1993). *Cucurbitella tricuspis* was very abundant in many samples. Presence of this species, known to have a planktic phase is not always indicative of lake bottom conditions (Schönborn, 1984; Patterson et al., 1985; Medioli et al. 1987; Collins et al. 1990). As the purpose of this research is to characterize benthic environments the Q-mode cluster analysis was carried out with C. tricuspis abundance data excluded (Figure 2).

R-Mode Analysis was performed on the 18 taxonomic units (Fig 3) found in statistically significant numbers (see Patterson and Fishbein, 1989). The methodology employed is the same as for Q-Mode analysis but is performed on taxonomic units rather than samples. This dendrogram was used to determine which species and strains tended to be found together, and is another useful method for identifying and assessing faunal associations.

JAMES LAKE PHYSIOGRAPHY AND GEOCHEMISTRY

James Lake is a narrow curved lake elongated in a north-south direction located along highway 11 north of Temagami in northeastern Ontario (Figure 1). The mesotrophic lake covering an area of 45.3 hectares [2] is fed by an inlet stream at the north end and drained by an outlet stream at the south end. The lake is divided into north (80%) and south (20%) basins separated by a narrows. The smaller southern basin is quite shallow, reaching a maximum depth of only 4.0 m. The northern basin with a maximum depth of 15.0 m (Figure 1) is sufficiently deep for summer stratification to occur. Both oxygen levels and temperature drop significantly below 5.0 m water depth. Temperature and oxygen levels in the upper epilimnion are 25° C and 9.0 mg/L, respectively during summer. Temperature and oxygen concentration drops to 10° C and 2.0 mg/L respectively in the lower hypolimnion.

The Keewatin age volcanic rocks along the southwest shore of the lake are quite rich in massive sulfides, particularly pyrite. Massive lens deposits of pyrite were discovered in within soft green schists in 1903. From February 1906, to March 1911the Northland Pyrite Mine Co. was operational, shipping more than 38,000 tons of pyrite to Cobalt, a short distance to the north. The pyrite was refined and used to make sulfuric acid, an essential ingredient in the milling of silver ore. Most mine waste rock (about 3,500 m^3 containing 25% pyrite with lesser amounts of pyrrhotite and traces of chalcopyrite and gold) was dumped on the southwest lakeshore. As rainwater percolates through the waste rock it becomes acidified. This process has contributed to acidification

of the adjacent lake water and bottom sediments. The water flow also leaches sulfates derived from the pyrite and pyrrhotite minerals.

In 1979 local residents began to express concern that seepage from the waste rock pile and open pit was having a detrimental effect on Granite Lake, a few hundred meters downstream from James Lake. There was also an increase in tourism to James Lake itself and the owners of a motel and a wilderness outfitter resort on the lake were worried about what impact continued leaching might have on water quality. For example iron staining has been visible on all rocks cropping out along the shore throughout the entire southern basin for many years (Gale, 1990). These rocks were still highly stained when we sampled the lake in 1996 and 1997 and on a subsequent visit in 1998.

A Ministry of the Environment (MOE) study began only two days after ice had left the lake on May 10, 1989, and continuing throughout that summer (Gale, 1990). Three key water quality parameters (iron, aluminum and sulfate) were found to exceed provincial guidelines in the MOE report. The results of our geochemical analysis also indicate that in pore waters as well only these three parameters exceed provincial guidelines.

In areas near the waste rock pile sulfate concentrations in the sediment are extremely high, up to 7500 μg/g. Sulfate ions and hydrogen ions from water interact to produce sulfuric acid. Localized bacterial reduction of some sulfate to H_2S may also contribute to development of a toxic benthic environment for many aquatic invertebrates (Environment Canada, 1979). During our sampling we observed a gradation from a low of pH (2.0) in some bottom sediments adjacent to the waste rock piles to almost neutral conditions (pH 6.8) in more distant areas of the southern basin of the lake. The position

of the outlet stream immediately adjacent to the mine site coupled with the overall north south flow of water in the lake helps maintain this gradient.

Several metals, most notably Al and Fe, are being leached out of the waste rock. Aluminum concentrations in pore water varied between 0.19 mg/L to 415 mg/L near the waste rock pile. Aluminum values in the lake water itself varied from 0.24 mg/L near the waste rock pile to 0.05 mg/L in the northern basin (Gale, 1990). Although Aluminum is not essential for survival it is found in almost all plant and animal species. Aluminum complexes into relatively stable complexes mostly unabsorbable by organisms in higher pH regimes (Plankey and Patterson, 1987, 1988). However, in lower pH environments (<pH 5.5) such as found in the southern basin of James Lake it mobilizes into biologically useable forms (Burrows, 1977). There are differing opinions as to the degree of hazard posed by aluminum in drinking water. Thus the guidelines for control of aluminum are highly variable. However, 0.2 mg/L seems to be the maximum allowable concentration agreed to by most agencies (Moore, 1991). In Canada and several European nations the guidelines for the protection of aquatic life are 0.1 mg/L at pH >6.5 and 0.005 mg/L at pH<6.5.

Sediment pore water iron levels vary from a high of 11,800 mg/L near the waste rock pile to only 1.52 mg/L in the northern basin. Iron concentration in lake water varies from 0.09 mg/L in the northern basin to 2.4 mg/L near the waste rock pile (Gale, 1990). The pH of the lake water rises to nearly neutral values throughout the lake during freshet and particularly during spring turnover (Gale, 1990). When near neutral water found in most parts of the lake mixes with acidic, metal-laden water near the waste dump, the metal precipitates out as iron hydroxide (FeOH). All measured pore water and lake water

iron concentration were found to be well in excess of the maximum value (0.3 mg/L) set by the Ontario provincial drinking water guideline. However, Iron is so plentiful in the environment that very high levels often accumulate in invertebrates. Since iron is an essential trace element, a certain amount of bioconcentration can occur with little ill effect (Vymazal, 1984; Tessier et al., 1984). Low drinking water guidelines are based primarily on aesthetics rather than any serious health concerns. As an example the taste of iron can readily be detected at 1.8 mg/L. High iron concentrations also lead to staining of laundry and plumbing and massive growth of bacteria in water systems (Moore, 1991). The recommended daily intake for men is 10 mg and 18 mg for women. Using the provincial guideline of 0.3 mg Fe/L H_2O the intake of iron from drinking water would be only 0.6 mg, far below the recommended human daily intake. Although guidelines for the protection for aquatic life range from 0.3 mg/L to 1.0 mg/L their tolerance is much higher (>10 mg/L; Moore, 1991). The observation by both Gale (1990) and ourselves of a large number of vertebrates (fish and amphibians) in the southern basin, corroborates this finding.

RESULTS AND DISCUSSION

James Lake provides a unique opportunity for assessing the sensitivity of arcellaceans to industrial pollutants (Kumar and Patterson, in press). Most small lakes in natural settings are characterized by a single environment (Smol, 1992). Paleolimnological studies therefore usually require proxy data collected from several lakes, each characterized by distinct environmental conditions and fauna. However, in James Lake the flow of lake water from north to south, exiting near the pollution point

source at the old mine site, has created habitats that range from unimpacted conditions in the northern basin to extremely contaminated conditions near the mine site itself. The gradation of environmental conditions in James Lake permits the more precise assessment of the limiting factors that control boundary states for arcellacean assemblages and individual taxa.

R-Mode Analysis

The results of the R-Mode cluster analysis revealed that the morphologically defined strains are useful for environmental discrimination in this lake as strains from the same species often did not cluster together (Figure 3). If the distribution of strains were not affected by environmental parameters it would be expected that R-mode cluster analysis would have grouped all the strains of one species together. Reinhardt et al., (1998) observed similar results in lakes from the nearby Cobalt area of Ontario where by using strains they were able to resolve subenvironments and faunal relationships that were otherwise unrecognizable.

Two species, *C. tricuspis* and *A. vulgaris* clustered distinctly from all the others in the R-Mode analysis (Figure 3). As discussed earlier when tests of the seasonally planktic C. tricuspis finally sink they tend to be equitably distributed around lakes in an assortment of environments much different from where they never actually lived (Schönborn, 1984; Patterson et al., 1985; Medioli et al. 1987; Collins et al. 1990). This species thus has no distinct association with any particular environment resulting in its isolated position in the R-mode cluster analysis.

Arcella vulgaris clustered distinctly from all other taxa because in the low pH samples where it dominates no other species can survive in appreciable numbers. *Arcella vulgaris* and *C. tricuspis* form a weak association in the R-mode analysis only because transported planktic *C. tricuspis* specimens are found in the same samples as *A. vulgaris*.

Q-Mode Analysis

Subjective interpretation of the Q-mode cluster analysis resulted in recognition of six assemblages, each characterized by a distinct fauna (Table 3).

***Arcella* Assemblage (1)**

The *Arcella* Assemblage (1) is restricted to the area immediately adjacent to the mine waste rock pile in the Southern Basin and is characterized by 7 samples (Table 1,3). With the exception of a large proportion of allochthonous *C. tricuspis* the fauna is almost exclusively comprised of *A. vulgaris*. The overall diversity of the various assemblages recognized in this study was determined by using the Shannon Diversity Index, defined as $H(S) = -p_i * \ln(p_i)$ where p_i is the proportion of the i^{th} species (and/or strains) in the assemblage. The Shannon Diversity Index is a better measure of diversity than numbers of species because it also takes into account the relative proportions of species in the population.

An extremely hostile habitat is indicated for the stations from where this assemblage was identified because of the extremely low diversity faunas identified (mean Shannon Diversity Index value (xSDI)=0.655) and generally low abundances. In contrast, healthy arcellacean faunas usually have Shannon Diversity Index values approaching 2.5 and abundances of near 500 specimens/cc. As in most stable climax

communities, there is an equitable distribution of species in these healthy environments with none overwhelmingly dominating the fauna. Various strains of *Difflugia oblonga* typically characterize these assemblages.

Although these samples were well oxygenated (5.9-8.8 mg/l at the sediment water interface) and found in warm water (up to 23.7°C at time of collection) they were all restricted to relatively shallow water depths (0.9 and 1.4 m) in silt and/or clay environments. Levels of iron and aluminum were very high in samples collected in the vicinity of the waste rock pile (Table 2). However, the most serious ecological constraint at stations where these samples were collected was probably the extremely low pH that varied between 2.6 and 5.7.

Higher Diversity *Arcella* Assemblage (2)

The Higher Diversity *Arcella* Assemblage (2) was also overwhelmingly dominated by *A. vulgaris*, after again deleting *C. tricuspis* distributional data (Table 1.3). It is also found adjacent to the waste rock pile under conditions similar to those characterizing the *Arcella* Assemblage and under pH conditions as low as 2.1. The only difference between the two assemblages is the presence of a low proportion of a few additional taxa most notably *Centropyxis aculeata* 'aculeata' and *Lesquereusia spiralis*. The Q-mode cluster analysis only grouped the Higher Diversity *Arcella* Assemblage more closely with samples from elsewhere in the lake because of the presence of at least some additional taxa (xSDI=1.079), as opposed to the monospecies distribution in the *Arcella* assemblage. As these assemblages are so similar they will be discussed together.

Arcella vulgaris dominates assemblages (90-100 %) found in the most contaminated areas of the lake in areas where pH is ≤ 5.7. However this species is almost totally absent in less contaminated regions where pH values of 6.5-7.5 were recorded (Table 1). A clue to the observed distribution of *A. vulgaris* can be provided by assessing its distribution in uncontaminated settings. The species is an important component of arcellacean faunas in boggy ponds in the Arctic and further south. The low pH values typical of these ponds has preadapted this species to dominate similar low pH environments. Other indications that pH may be the dominant controlling factor on arcellacean distribution in these assemblages, rather that elevated Al or Fe levels, is the greatly reduced presence of opportunistic centropyxid taxa. In higher pH environments in the Cobalt area strains of species such as *C. aculeata* dominate contaminated substrates (Patterson, et al., 1996; Reinhardt et al., 1998).

Also notably missing from these lower pH environments of this lake are any strains of *Difflugia protaeiformis*, although the species is often abundant in portions of James Lake with pH of 6.5-7.5, and in higher pH and highly contaminated areas of Peterson and Crosswise lakes.

***Difflugia* Assemblage (3)**

The *Difflugia* Assemblage characterizes 10 samples in relatively shallow water (x=1.7m) from higher pH area (x=6.7) of both the southern and northern basin of James Lake on a variety of muddy to silty substrates (Table 1,3). The fauna is very diverse and equitably distributed (xSDI=2.364). Excluding *C. tricuspis* from consideration the fauna is dominated by varying strains of *Difflugia oblonga*, most notably *D. oblonga*

"lithophila" (x=13.9) and *D. oblonga* "glans" (x=11.1). Dominance of difflugids is generally associated with high levels of organic content in the substrate (Collins et al., 1990). The high diversity and great abundance of arcellaceans found at these sites also indicates an abundant source of organics sufficient to maintain a habitat with high carrying capacity. Variants of this assemblage are common in eutrophic lakes throughout eastern North America (Patterson et al., 1985; Collins et al., 1990; Patterson et al., 1996). The very high proportions of *C. tricuspis* in the lake, associated with various algal species such as *Spyrogyra* and known to bloom under eutrophic conditions (Collins et al., 1990), corroborate this assessment.

***Difflugia protaeiformis* Assemblage (4)**

The *Difflugia protaeiformis* Assemblage was only found in two samples, 96JL5 and 96JL24, found in close approximation to each other in the northern part of the lake (Table 1,3). The lake substrate consisted of clay at these sites, varying between 4.2 and 5.5 m water depth. The sites were well oxygenated (7.2-7.7 mg/l) with near neutral pH values. The arcellacean fauna found in this assemblage was diverse (xSDI=2.268), although excluding *C. tricuspis* only one strain *D. protaeiformis* "amphoralis" (x=22.9%) was really dominant, followed by *Lesquereusia spiralis* (x=9.1%), *D. protaeiformis* "claviformis" (8.6%) and *D. protaeiformis* "acuminata" (x=5.5%). Dominance of *D. protaeiformis* strains in an assemblage has generally been related to either polluted or stressed environments in northern Ontario and Italy (Asioli et al., 1996; Reinhardt et al., 1998). Reinhardt et al found that *D. protaeiformis* "claviformis" comprised nearly 60% of the fauna in highly contaminated raw tailings substrates in Peterson Lake near Cobalt

Ontario. However, water and substrate quality in the northern part of James Lake is very good. It is interesting to note that Reinhardt et al. (1998) also reported relatively high proportions of *D. protaeiformis* "amphoralis and *D. protaeiformis* "acuminata" (up to 10%) on muddy substrates, particularly those characterized by high numbers of pennate diatoms. It is quite significant that the muds characterizing the substrate where these samples were collected also had very high diatom abundances. These results seem to indicate that while high proportions of some strains of *D. protaeiformis* are key indicators of normal pH and highly contaminated conditions some strains are more characteristic of the host substrate. It is plausible that *D. protaeiformis* "amphoralis" and *D. protaeiformis* "acuminata" preferentially graze on pennate diatoms and their abundance in this part of the lake is related to ample supplies of a preferred food source.

***Lesquereusia* Assemblage (5)**

The *Lesquereusia* Assemblage is quite similar the *Difflugia* Assemblage in diversity (xSDI=2.386), preferred substrate pH (x=6.8) and distribution in both the southern and northern parts of James Lake (Table 1,3). As with the *Difflugia* Assemblage the high diversity and high specimen counts from this assemblage reflects a high organic content in the substrate. The *Lesquereusia* Assemblage is found in slightly deeper water though (x=2.4m) and unlike the *Difflugia* Assemblage no single species is overwhelmingly dominant, except of course for *C. tricuspis*. The most abundant species is *Lesquereusia spiralis* (x=10.0). Substrate may be an important control over the distribution of this species as highest abundances were associated with sandier substrates. There has unfortunately been very little research done on the distribution of *L. spiralis*

with the exception of results indicating that the species prefers temperate lakes and is generally not common in polar regions.

There were three sample cluster misclassifications associated with this Assemblage. Samples 96JL-4, 96JL-23, and 97JL-1 were collected from between 9.8 and 14.1m of water, well below the thermocline depth (5 m) under very low oxygen (1.4 mg/l) and temperature (7-9°C) conditions. This environment is not conducive to arcellacea and faunas examined in similar lakes from beneath the thermocline are invariable low diversity and depauperate (Patterson et al., 1985; Patterson et al., 1996). The presence of a diverse fauna here probably indicates that some reworking of material from shallower water has occurred.

***Centropyxis* Assemblage (6)**

The *Centropyxis* Assemblage was comprised of only a single sample (97JL-11) from near the narrows separating the northern and southern portions of James Lake in 1.5m of water under high oxygenation levels (8.0) and near neutral pH (6.4; Table 1,3). Although diverse (xSDI=2.321) the fauna is overwhelmingly dominated by two strains of *C. aculeata* (*C. aculeata* "aculeata" and *C. aculeata* "discoides"). Centropyxids are opportunistic species and faunas dominated by these species are typically stressed. For example, in the Cobalt region Centropyxid dominated faunas are typical of highly metal contaminated lake environments under near neutral pH conditions. The presence of this fauna here is enigmatic. This portion of the lake is well away from the contaminated regions of the lake near the mine site and although near a commercial lodge the only potential source of pollutants from that site would be sewage. The influx of organics

would have caused a spike in difflugids not centropyxids. Recovery of more than a single sample characterized by this fauna is required to ascertain the validity of this assemblage.

ACKNOWLEDGMENTS

This research was supported by NSERC Research Grant OGP 0041665 to RTP. We also gratefully acknowledge the assistance of students in the Department of Earth Sciences Environmental Geology Field Camp (67.285) for their help in the field.

REFERENCES

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.

Burrows, W. D., 1977 . Aquatic aluminum: chemistry, toxicology and environmental prevalence. CRC Crit. Rev. Environ. Control, 7: 167-216.

Campbell, P.G.C., 1995. Interactions between trace metals and aquatic organisms: a critique of the free-ion activity model. In: Metal Speciation and Bioavailability in Aquatic Systems. A. Tessier, and D.R. Turner (eds.) John Wiley & Sons Ltd.

Collins, E.S., McCarthy, F.M., Medioli, F.S., Scott, D.B. and Honig, C.A., 1990. Biogeographic distribution of modern thecamoebians in a transact along the eastern North American coast, in Hemleben, C., Kaminski, M.A., Kuhnt, W. and Scott, D.B. eds., Paleoecology, Biostratigraphy, Paleoceanography and Taxonomy of Agglutinated Foraminifera: NATO Advanced Study Institute Series, Series C, Mathematical and Physical Sciences, 327:783-791.

Environment Canada, 1979. Water Quality Source Book.

Fishbein, E. and Patterson, R. T., 1993. Error-weighted maximum likelihood (EWML): a new statistically based method to cluster quantitative micropaleontological data. Journal of Paleontology, 67:475-485.

Gale, P., 1990. James Lake, Northland Pyrite Mine. Ontario Department of the Environment Technical Memorandum. Sudbury Ontario. 15 p.

Kumar, A. and Dalby, A.P., 1998. Identification key for Holocene lacustrine arcellacean (thecamoebian) taxa. Palaeontologia Electronica, 1: 39 p.

Kumar, A., and Patterson, R.T. (in press) Arcellaceans (Thecamoebians): New Tools For Monitoring Long And Short Term Changes In Lake Bottom Acidity. Environmental Geology

Luoma, S.N.1983. Bioavailability of trace metals to aquatic organisms—a review. Science of the Total Environment, 28:1 -22.

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. and Scott, D.B., 1988. Lacustrine thecamoebians (mainly Arcellaceans) as potential tools for paleolimnological interpretations. Paleogeography, Paleoclimatology, Paleoecology, 62: 361-386.

Moore, J.W., 1991. Inorganic Contaminants of Surface Water: Research and Monitoring Priorities. New York: Springer-Verlag, 334p.

Mosteller, F., Rourke, K.E. and Thomas, G.B., Jr., 1970. Probability and Statistical Applications. Don Mills: Addison-Wesley, 527 p.

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: 14-137.

Patterson, R.T. and Fishbein, E., 1989. Re-examination of the statistical methods used to determine the number of point counts needed for micropaleontological quantitative research. Journal of Paleontology, 63: 245-248.

Patterson, R.T. and Kumar, A. (in press) Use of Arcellacea to gauge levels of pollution and remediation of industrially polluted lakes in Martin, R.E. (Ed) Environmental Micropaleontology. Plenum Press.

Patterson, R. T., Barker, T. and Burbridge, S. M., 1996. Arcellaceans (Thecamoebians)as proxies of arsenic and mercury contamination in northeastern Ontario lakes. Journal of Foraminiferal Research. 26: 172- 183.

Plankey, B. J. and Patterson, H. H.,1987. Kinetics of aluminum fulvic acid complexation in acidic waters. Env. Sci. Tech., 21:595-601.

Plankey, B. J. and Patterson, H. H., 1988. Effect of fulvic acid on the kinetics of aluminum fluoride complexation in acidic waters. Env. Sci. Tech., 22:1454-1456.

Reinhardt, E.G., Dalby, A.P., Kumar, A., and Patterson, R.T. 1998. Arcellaceans as pollution indicators in mine tailing contaminated lakes near Cobalt, Ontario, Canada. Micropaleontology 44:1-18.

Schönborn, W.S., 1984. Studies on remains of Testacea in cores of the Great Woryty Lake (NE-Poland). Limnologica (Berlin), 16: 185- 190.

Scott, D. B. and Hermelin, J. O. R., 1993. A device for precision splitting of micropaleontological samples in liquid suspension. Journal of Paleontology. 67:

151-154.

Smol, J.P. 1992. Paleolimnology: an important tool for effective ecosystem management. Journal of Aquatic Ecosystem Health, 1: 49-58.

Tessier, A., Campbell, P. G. C., Auclair, J. C. and Bisson, M., 1984.relationships between the partitioning of trace metals in sediments and their accumulation in the tissues of the fresh water mollusk *Elliptio complanata* in a mining area. Canadian Journal of Fisheries and Aquatic Science. 41: 1463-1472.

Vymazal, J. 1984. Short term uptake of heavy metals by periphyton algae. Hydrobiologia, 119: 171-179.

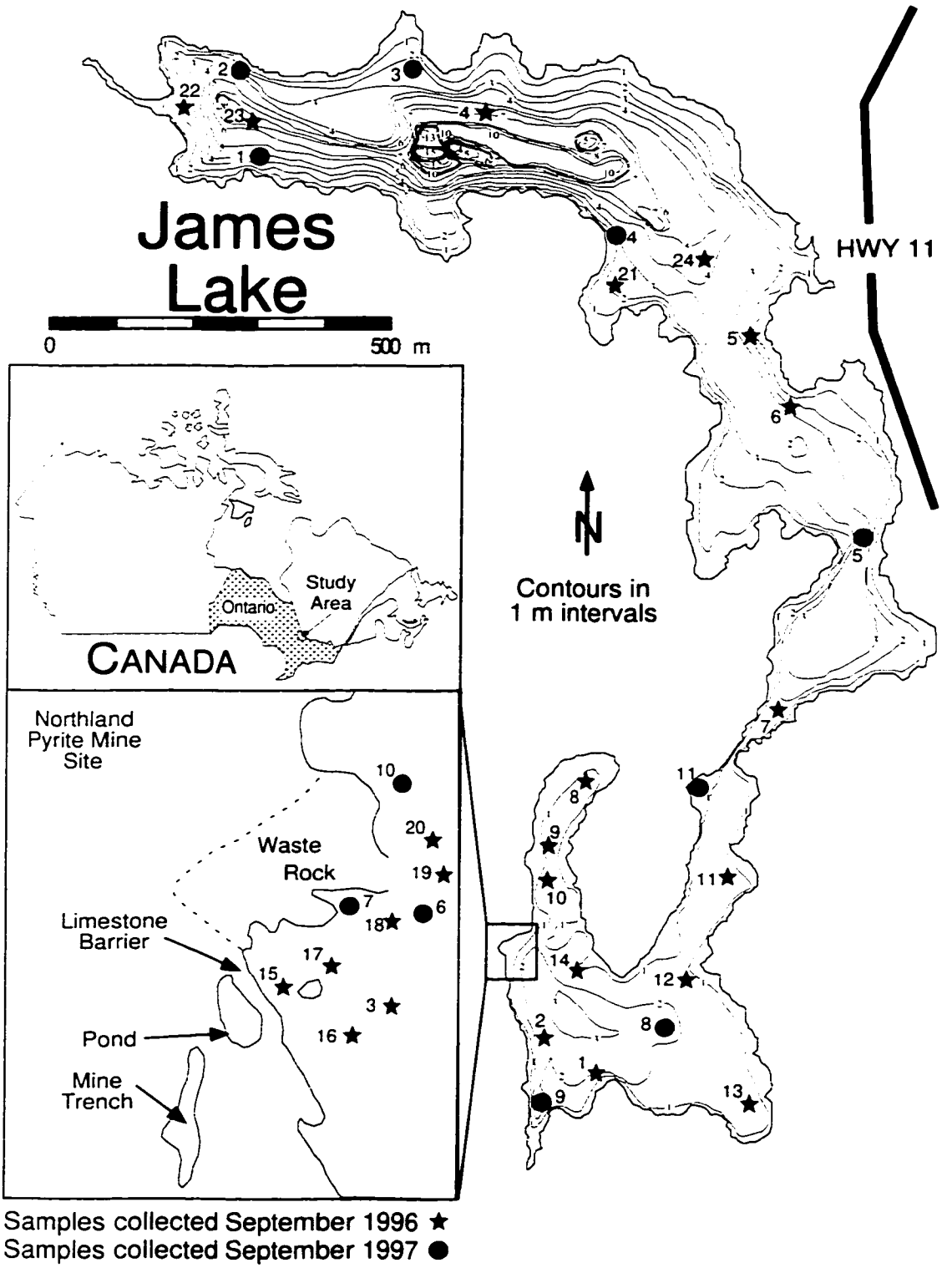
Figures in Text

Tables in Text

Table 1. Arcellacean occurrences in samples from James Lake. Samples were quantitatively analyzed and are recorded as fractional abundances. Total counts, water depth, assemblage designation, Shannon Diversity, and various other physiographic parameters are also indicated.

Table 2. Pore-water pH and geochemistry values for Al, Fe and sulfate in mg/L from selected sample stations. Al and Fe values determined by microwave digestion for inductively coupled plasma atomic emission spectroscopy (ICP-AES) and granite furnace atomic absorption spectroscopy (GFAAS, 26 element scan). Sulfate values were determined by ion chromatography.

Table 3. Mean fractional abundances and various parameters characterizing the six arcellacean assemblages identified in James Lake.


James Lake
0
500 m
HWY 11
Contours in 1 m intervals
N
Ontario
Study Area
CANADA
Northland Pyrite Mine Site
Waste Rock
Limestone Barrier
Pond
Mine Trench
Samples collected September 1996 ★
Samples collected September 1997 ●

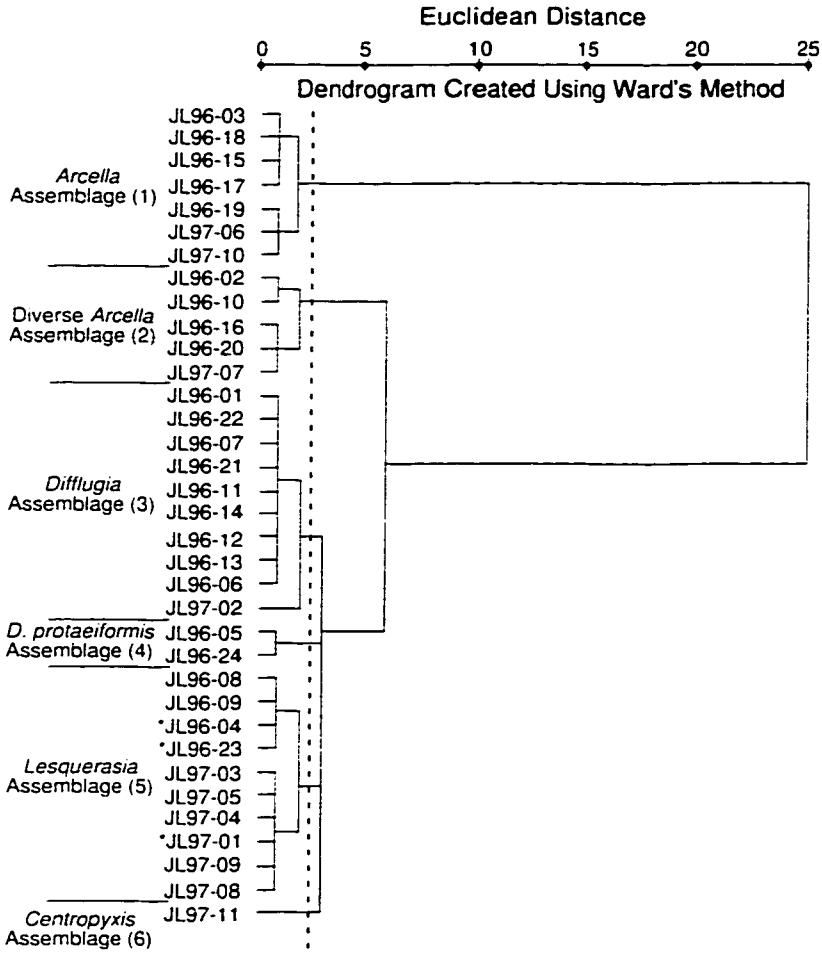

Euclidean Distance
0
5
10
15
20
25
Dendrogram Created Using Ward's Method
JL96-03
JL96-18
JL96-15
JL96-17
JL96-19
JL97-06
JL97-10
JL96-02
JL96-10
JL96-16
JL96-20
JL97-07
JL96-01
JL96-22
JL96-07
JL96-21
JL96-11
JL96-14
JL96-12
JL96-13
JL96-06
JL97-02
JL96-05
JL96-24
JL96-08
JL96-09
*JL96-04
*JL96-23
JL97-03
JL97-05
JL97-04
*JL97-01
JL97-09
JL97-08
JL97-11
Arcella Assemblage (1)
Diverse Arcella Assemblage (2)
Difflugia Assemblage (3)
D. protaeiformis Assemblage (4)
Lesquerasia Assemblage (5)
Centropyxis Assemblage (6)

Figure 3

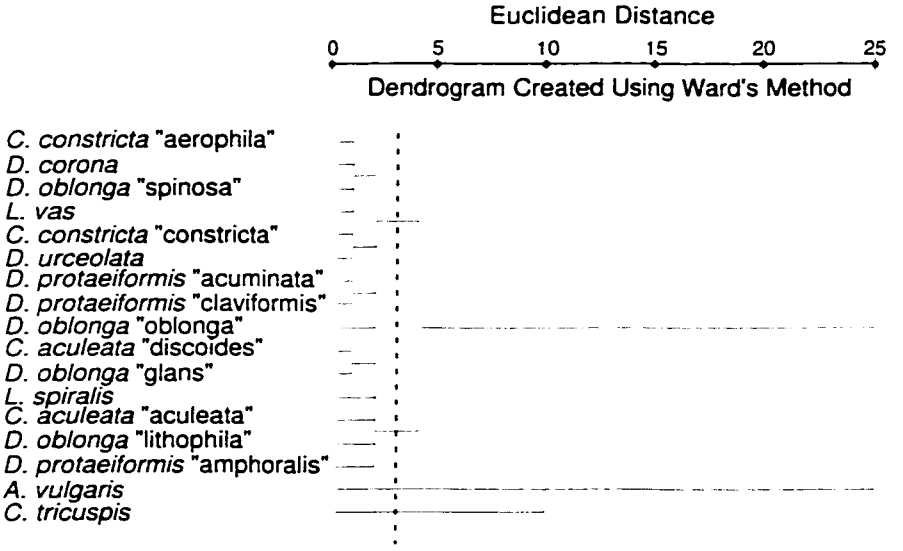

Euclidean Distance
0
5
10
15
20
25
Dendrogram Created Using Ward's Method
C. constricta "aerophila"
D. corona
D. oblonga "spinosa"
L. vas
C. constricta "constricta"
D. urceolata
D. protaeiformis "acuminata"
D. protaeiformis "claviformis"
D. oblonga "oblonga"
C. aculeata "discoides"
D. oblonga "glans"
L. spiralis
C. aculeata "aculeata"
D. oblonga "lithophila"
D. protaeiformis "amphoralis"
A. vulgaris
C. tricuspis

Table 1

Sample	JL96-1	JL96-2	JL96-3	JL96-4	JL96-5	JL96-6	JL96-7	JL96-8	JL96-9	JL96-10	JL96-11	JL96-12	JL96-13	JL96-14	JL96-15	JL96-16	JL96-17	JL96-18	JL96-19	JL96-20	JL96-21	JL96-22	JL96-23	JL96-24	JL97-1	JL97-2	JL97-3	JL97-4	JL97-5	JL97-6	JL97-7	JL97-8	JL97-9	JL97-10	JL97-11
Total Count	221	201	271	531	515	513	505	510	528	525	515	511	506	505	539	410	572	511	510	507	506	541	548	512	526	548	506	518	547	547	507	552	529	89	561
Species/Act	74	67	90	177	144	228	224	207	128	130	210	138	230	205	226	136	58	124	207	205	204	541	233	208	218	232	153	318	232	294	307	235	132	178	242
Shannon Diversity	2.422	0.784	0.718	1.402	2.339	2.256	2.419	2.348	2.097	0.772	2.154	2.364	2.302	2.351	0.719	0.803	0.625	0.912	0.542	1.466	2.392	2.358	1.629	2.196	2.193	2.480	2.483	2.426	2.487	0.615	1.572	2.398	2.462	0.454	2.321
Number of Species	16	6	4	16	18	16	17	17	18	5	18	18	19	19	9	11	3	10	2	11	19	18	14	17	17	19	20	19	20	3	11	20	17	2	18
Assemblage	3	2	1	.	4	3	3	5	5	2	3	4	3	3	1	2	1	1	1	2	3	3	.	4	.	3	5	5	5	1	2	5	5	1	6
Water Depth (m)	1.8	2.6	0.9	9.8	4.2	2.4	1	1.8	1.4	0.6	1.4	0.9	1.1	1.1	1.1	0.8	1	0.8	1.1	0.7	1	3	0.7	5.5	7.8	3	3.9	3.1	1.5	1.4	0.7	1.4	1.6	1.1	1.5
Sediment/Water Interface pH	6.7	3.9	3.9	7.1	6.9	7.3	6.5	6.9	6.5	2.5	6.5	6.6	6.7	6.7	2.6	2.1	4.1	5.1	5.5	2.2	6.4	6.7	.	6.7	6.7	7	7.3	7.1	6.6	5.7	4.3	6.6	6.1	4.4	6.4
Sediment/Water Interface O2	8.2	5.6	6.9	1.4	7.5	7.4	7.1	6	7.3	7.4	7.2	7.4	7.4	7.4	6.9	6.1	7.4	6.9	5.9	5.2	6.8	7.1	8.9	7.2	2.4	.	8.1	8.1	8.6	8.8	8.4	8.1	8.2	7.9	8
Sediment/Water Interface Temperatur	20.7	20.4	21	6.7	20.3	20.8	20.8	21.3	21.4	21.5	21.5	22.1	21.5	22.5	22.9	23.4	23.4	23.7	23.9	25	22.7	20.7	.	19	.	17.5	17.1	17.7	17.1	16.8	17.1	17	.	.	18
Sediment Texture	Mud	Mud	Mud	Sd/Md	Mud	Mud	Sd/Md	Mud	Sd/Md	Snd/Md	Sd/Md	Snd/Md	Snd/Md	Mud	Sd/Md	Snd/Md	Sdt	Snd/Md	Mud	Mud	Mud	Mud	Mud	Mud	Mud	Mud	Sd/Md	Fn Snd	Fn Snd	Mud	Mud	Mud	Mud	Pebb Md	Sd/Md
Arcella vulgaris	13	68	158	14	4	5	3	12	9	155	4	1	2	1	216	59	117	189	238	35	1	1	26	7	52	3	12	11	6	107	129	5	15	74	5
percent (%)	0.059	0.338	0.583	0.026	0.008	0.010	0.006	0.039	0.027	0.477	0.013	0.003	0.006	0.003	0.637	0.144	0.680	0.698	0.768	0.114	0.003	0.002	0.075	0.022	0.098	0.009	0.039	0.035	0.017	0.728	0.254	0.014	0.046	0.831	0.014
standard error (±)	0.031	0.065	0.059	0.014	0.008	0.009	0.007	0.021	0.018	0.054	0.012	0.006	0.008	0.006	0.051	0.034	0.070	0.054	0.047	0.036	0.006	0.004	0.028	0.016	0.032	0.010	0.022	0.020	0.014	0.072	0.038	0.012	0.023	0.078	0.012
Centropyxis aculeata "aculeata"	7	1	0	11	6	11	25	22	29	1	21	20	12	17	0	5	0	1	0	34	19	24	11	4	20	21	10	20	9	0	29	19	15	0	90
percent (%)	0.032	0.005	0.000	0.021	0.012	0.021	0.050	0.071	0.088	0.003	0.067	0.064	0.035	0.056	0.000	0.012	0.000	0.003	0.000	0.111	0.062	0.044	0.032	0.013	0.061	0.042	0.033	0.063	0.026	0.000	0.057	0.054	0.046	0.000	0.248
standard error (±)	0.023	0.010	0.000	0.012	0.009	0.013	0.019	0.029	0.031	0.006	0.028	0.027	0.019	0.026	0.000	0.011	0.000	0.006	0.000	0.035	0.027	0.017	0.018	0.012	0.026	0.025	0.020	0.027	0.017	0.000	0.020	0.024	0.023	0.000	0.044
Centropyxis aculeata "discoides"	15	2	0	11	21	36	44	12	8	0	21	14	34	20	0	1	0	3	0	16	32	74	16	9	37	12	20	13	14	0	10	41	17	0	54
percent (%)	0.068	0.010	0.000	0.021	0.041	0.070	0.087	0.019	0.024	0.000	0.067	0.045	0.098	0.066	0.000	0.002	0.000	0.010	0.000	0.052	0.105	0.137	0.046	0.029	0.113	0.034	0.065	0.041	0.040	0.000	0.020	0.116	0.112	0.000	0.149
standard error (±)	0.033	0.014	0.000	0.012	0.017	0.022	0.025	0.021	0.017	0.000	0.028	0.021	0.031	0.028	0.000	0.005	0.000	0.011	0.000	0.025	0.034	0.029	0.022	0.019	0.034	0.019	0.028	0.022	0.021	0.000	0.012	0.034	0.034	0.000	0.049
Centropyxis constricta "spinosa"	1	0	0	7	1	0	0	2	5	1	4	4	6	1	0	1	2	0	0	2	8	2	1	1	0	1	1	1	0	0	0	0	0	0	0
percent (%)	0.014	0.000	0.000	0.013	0.002	0.000	0.000	0.006	0.015	0.003	0.011	0.013	0.017	0.010	0.000	0.007	0.012	0.000	0.000	0.007	0.026	0.004	0.003	0.003	0.000	0.003	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
standard error (±)	0.015	0.000	0.000	0.010	0.003	0.000	0.000	0.009	0.013	0.006	0.012	0.013	0.014	0.011	0.000	0.008	0.016	0.000	0.000	0.009	0.018	0.005	0.006	0.006	0.000	0.006	0.006	0.006	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Centropyxis constricta "constricta"	29	0	0	0	29	38	24	16	15	0	27	15	40	18	0	0	0	0	0	0	19	29	0	12	14	19	20	15	16	0	0	30	7	0	15
percent (%)	0.131	0.000	0.000	0.000	0.056	0.074	0.048	0.032	0.036	0.000	0.066	0.048	0.116	0.059	0.000	0.000	0.000	0.000	0.000	0.000	0.062	0.054	0.000	0.038	0.041	0.055	0.065	0.047	0.046	0.000	0.000	0.085	0.021	0.000	0.041
standard error (±)	0.045	0.000	0.000	0.000	0.020	0.023	0.019	0.025	0.023	0.000	0.031	0.024	0.034	0.026	0.000	0.000	0.000	0.000	0.000	0.000	0.027	0.019	0.000	0.021	0.022	0.024	0.028	0.023	0.022	0.000	0.000	0.029	0.016	0.000	0.020
Centropyxis constricta "aerophila"	14	0	0	0	4	0	2	1	3	0	7	9	8	3	0	0	0	0	0	0	7	13	2	1	7	0	3	4	6	0	7	9	15	0	6
percent (%)	0.063	0.000	0.000	0.000	0.008	0.000	0.004	0.003	0.015	0.000	0.022	0.029	0.023	0.016	0.000	0.000	0.000	0.000	0.000	0.000	0.023	0.024	0.006	0.003	0.021	0.000	0.010	0.013	0.017	0.000	0.014	0.026	0.046	0.000	0.017
standard error (±)	0.032	0.000	0.000	0.000	0.008	0.000	0.005	0.006	0.013	0.000	0.016	0.019	0.016	0.014	0.000	0.000	0.000	0.000	0.000	0.000	0.017	0.013	0.008	0.006	0.016	0.000	0.011	0.012	0.014	0.000	0.010	0.016	0.023	0.000	0.011
Cucurbitella tricuspis	20	126	107	143	82	84	81	96	127	162	63	69	52	77	119	316	53	107	72	169	46	21	194	62	81	51	63	73	71	38	237	96	99	15	48
percent (%)	0.090	0.627	0.395	0.646	0.159	0.164	0.160	0.310	0.387	0.498	0.200	0.222	0.150	0.252	0.451	0.771	0.308	0.344	0.232	0.550	0.150	0.039	0.557	0.199	0.248	0.089	0.199	0.230	0.205	0.259	0.467	0.271	0.301	0.169	0.192
standard error (±)	0.038	0.067	0.058	0.041	0.032	0.032	0.032	0.051	0.053	0.054	0.044	0.046	0.038	0.049	0.051	0.043	0.069	0.053	0.047	0.056	0.040	0.016	0.052	0.044	0.047	0.030	0.045	0.046	0.042	0.071	0.043	0.047	0.050	0.078	0.035
Difflugia corona	7	1	2	2	11	8	14	12	3	4	14	11	8	12	0	3	0	1	0	0	4	11	2	3	11	1	8	8	10	1	8	10	11	0	1
percent (%)	0.032	0.005	0.007	0.004	0.021	0.016	0.028	0.039	0.009	0.012	0.044	0.035	0.023	0.039	0.000	0.007	0.000	0.003	0.000	0.000	0.013	0.020	0.006	0.010	0.034	0.005	0.026	0.025	0.029	0.007	0.016	0.028	0.033	0.000	0.003
standard error (±)	0.023	0.010	0.010	0.005	0.012	0.013	0.014	0.021	0.010	0.012	0.023	0.021	0.016	0.022	0.000	0.008	0.000	0.006	0.000	0.000	0.013	0.012	0.008	0.011	0.020	0.006	0.018	0.017	0.018	0.013	0.011	0.017	0.019	0.000	0.005
Difflugia oblonga "glans"	30	0	0	41	50	49	59	27	27	0	35	35	36	33	0	5	0	2	0	2	31	85	13	31	15	22	23	19	24	0	0	37	27	0	21
percent (%)	0.136	0.000	0.000	0.077	0.097	0.096	0.117	0.087	0.082	0.000	0.111	0.113	0.104	0.108	0.000	0.012	0.000	0.006	0.000	0.007	0.101	0.157	0.037	0.099	0.046	0.061	0.075	0.060	0.069	0.000	0.000	0.105	0.082	0.000	0.058
standard error (±)	0.045	0.000	0.000	0.023	0.026	0.025	0.028	0.021	0.020	0.000	0.035	0.033	0.032	0.035	0.000	0.013	0.000	0.009	0.000	0.009	0.034	0.031	0.020	0.033	0.023	0.026	0.030	0.026	0.027	0.000	0.000	0.032	0.030	0.000	0.024
Difflugia oblonga "lineata"	5	0	2	1	7	17	5	0	1	0	9	1	12	2	0	1	0	0	0	0	12	12	1	6	0	8	1	0	1	0	0	1	0	0	0
percent (%)	0.023	0.000	0.007	0.002	0.014	0.033	0.010	0.000	0.003	0.000	0.029	0.003	0.019	0.007	0.000	0.002	0.000	0.000	0.000	0.000	0.019	0.059	0.001	0.019	0.000	0.023	0.003	0.000	0.001	0.000	0.000	0.003	0.000	0.000	0.000
standard error (±)	0.020	0.000	0.010	0.004	0.010	0.015	0.009	0.000	0.006	0.000	0.018	0.006	0.019	0.009	0.000	0.005	0.000	0.000	0.000	0.000	0.022	0.020	0.006	0.015	0.000	0.016	0.006	0.000	0.006	0.000	0.000	0.006	0.000	0.000	0.000
Difflugia oblonga "lithophila"	29	0	0	9	34	129	81	30	14	0	35	36	50	32	0	0	0	2	0	0	32	85	0	17	3	37	7	12	3	0	0	13	1	0	5
percent (%)	0.131	0.000	0.000	0.017	0.066	0.251	0.160	0.059	0.027	0.000	0.111	0.116	0.149	0.105	0.000	0.000	0.000	0.006	0.000	0.000	0.105	0.157	0.000	0.054	0.009	0.106	0.023	0.038	0.009	0.000	0.000	0.047	0.003	0.000	0.014
standard error (±)	0.045	0.000	0.000	0.011	0.021	0.038	0.032	0.013	0.022	0.000	0.035	0.036	0.037	0.034	0.000	0.000	0.000	0.009	0.000	0.000	0.034	0.031	0.000	0.025	0.010	0.032	0.017	0.021	0.010	0.000	0.000	0.020	0.006	0.000	0.012
Difflugia oblonga "oblonga"	6	0	0	7	17	13	18	5	2	0	6	3	7	5	1	0	0	0	0	0	9	9	17	2	0	0	81	12	1	11	0	22	4	6	0	0
percent (%)	0.027	0.000	0.000	0.013	0.033	0.025	0.036	0.016	0.006	0.000	0.019	0.010	0.020	0.016	0.003	0.000	0.000	0.000	0.000	0.029	0.029	0.068	0.006	0.000	0.000	0.233	0.019	0.003	0.012	0.000	0.000	0.043	0.011	0.018	0.000
standard error (±)	0.021	0.000	0.000	0.010	0.015	0.014	0.016	0.014	0.008	0.000	0.015	0.011	0.015	0.014	0.006	0.000	0.000	0.000	0.000	0.019	0.019	0.021	0.008	0.000	0.000	0.044	0.022	0.006	0.018	0.000	0.000	0.018	0.011	0.014	0.000
Difflugia oblonga "spinosa	0	0	0	3	9	9	8	4	0	0	1	0	1	3	0	0	0	0	0	0	5	12	0	3	3	17	1	2	4	0	0	5	4	0	3
percent (%)	0.000	0.000	0.000	0.006	0.017	0.018	0.016	0.013	0.000	0.000	0.003	0.000	0.003	0.010	0.000	0.000	0.000	0.000	0.000	0.000	0.016	0.022	0.000	0.010	0.009	0.049	0.003	0.006	0.012	0.000	0.000	0.014	0.012	0.000	0.008
standard error (±)	0.000	0.000	0.000	0.006	0.011	0.011	0.011	0.013	0.000	0.000	0.006	0.000	0.006	0.011	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.012	0.000	0.011	0.010	0.021	0.006	0.009	0.011	0.000	0.000	0.012	0.012	0.000	0.009
Difflugia protaeiformis "acuminata"	3	0	0	21	29	26	37	20	26	0	12	16	7	14	1	1	0	3	0	4	20	23	19	17	8	19	24	37	26	0	8	19	20	0	17
percent (%)	0.014	0.000	0.000	0.040	0.056	0.051	0.073	0.065	0.079	0.000	0.038	0.051	0.020	0.046	0.003	0.002	0.000	0.010	0.000	0.015	0.065	0.043	0.055	0.054	0.025	0.055	0.078	0.116	0.075	0.000	0.016	0.028	0.061	0.000	0.047
standard error (±)	0.015	0.000	0.000	0.017	0.020	0.019	0.023	0.022	0.029	0.000	0.021	0.025	0.015	0.023	0.006	0.005	0.000	0.011	0.000	0.013	0.028	0.017	0.024	0.025	0.017	0.024	0.030	0.035	0.028	0.000	0.011	0.017	0.026	0.000	0.022
Difflugia protaeiformis "angulosalis"	0	0	0	17	122	28	16	5	10	0	11	19	9	8	0	0	0	1	0	0	8	6	28	69	13	8	23	22	33	0	0	3	11	0	16
percent (%)	0.000	0.000	0.000	0.032	0.237	0.055	0.071	0.016	0.030	0.000	0.035	0.061	0.026	0.026	0.000	0.000	0.000	0.003	0.000	0.000	0.026	0.011	0.080	0.221	0.040	0.021	0.075	0.069	0.095	0.000	0.000	0.009	0.033	0.000	0.044
standard error (±)	0.000	0.000	0.000	0.015	0.037	0.020	0.022	0.014	0.019	0.000	0.020	0.027	0.017	0.018	0.000	0.000	0.000	0.006	0.000	0.000	0.018	0.009	0.029	0.046	0.021	0.016	0.030	0.028	0.031	0.000	0.000	0.010	0.019	0.000	0.021
Difflugia protaeiformis "claviformis"	7	0	0	8	21	8	9	15	11	0	0	9	6	8	0	0	0	0	0	0	3	17	20	12	41	8	14	17	3	15	0	0	4	12	0	10
percent (%)	0.032	0.000	0.000	0.015	0.041	0.016	0.018	0.048	0.040	0.000	0.000	0.029	0.017	0.026	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.056	0.037	0.034	0.131	0.025	0.040	0.056	0.009	0.043	0.000	0.000	0.011	0.036	0.000
standard error (±)	0.023	0.000	0.000	0.010	0.017	0.011	0.012	0.024	0.021	0.000	0.000	0.019	0.014	0.018	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.026	0.016	0.019	0.037	0.017	0.021	0.026	0.011	0.021	0.000	0.000	0.011	0.020	0.000
Difflugia urceolata	25	0	0	1	13	11	12	12	10	0	17	13	20	17	0	3	0	0	0	3	7	30	0	3	19	13	7	13	20	0	0	25	12	0	13
percent (%)	0.113	0.000	0.000	0.002	0.025	0.021	0.024	0.039	0.030	0.000	0.054	0.042	0.058	0.056	0.000	0.012	0.000	0.000	0.000	0.001	0.023	0.092	0.000	0.010	0.058	0.037	0.023	0.041	0.058	0.000	0.000	0.071	0.036	0.000	0.036
standard error (±)	0.042	0.000	0.000	0.004	0.014	0.013	0.013	0.021	0.019	0.000	0.025	0.022	0.025	0.026	0.000	0.011	0.000	0.000	0.000	0.006	0.017	0.024	0.000	0.011	0.025	0.020	0.017	0.022	0.025	0.000	0.000	0.027	0.020	0.000	0.019
Lagenodifflugia sp.	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	6	8	15	21	0	11	22	13	0	34
percent (%)	0.018	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.037	0.017	0.026	0.047	0.061	0.000	0.022	0.063	0.040	0.000	0.044
standard error (±)	0.018	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.020	0.014	0.018	0.023	0.025	0.000	0.011	0.025	0.021	0.000	0.030
Lequereusia spiralis	4	1	0	14	51	39	46	19	19	0	25	31	27	24	2	11	0	2	0	12	25	17	21	26	36	11	19	46	50	0	46	17	14	0	21
percent (%)	0.018	0.005	0.000	0.064	0.099	0.076	0.091	0.061	0.058	0.000	0.079	0.100	0.078	0.079	0.006	0.027	0.000	0.006	0.000	0.004	0.082	0.031	0.060	0.083	0.110	0.089	0.127	0.145	0.144	0.000	0.091	0.048	0.101	0.000	0.058
standard error (±)	0.018	0.010	0.000	0.021	0.026	0.021	0.025	0.027	0.025	0.000	0.030	0.033	0.028	0.030	0.008	0.016	0.000	0.009	0.000	0.014	0.031	0.015	0.025	0.031	0.034	0.030	0.037	0.039	0.037	0.000	0.025	0.022	0.033	0.000	0.024

Sample	pH	Al (mg/L)	Fe (mg/L)	Sulfate (mg/L)
JL 97-2	6.73	0.46	2.44	7.5
JL 97-3	6.51	0.38	2.84	7.5
JL 97-4	6.55	0.37	2.36	9.2
JL 97-5	6.33	0.19	1.52	12.4
JL 97-6	2.49	64	1240	2884
JL 97-7	2.12	415	11800	17238
JL 97-8	6.24	1.11	59.7	9.9
JL 97-9	5.56	0.94	64.9	25.2
JL 97-10	2.69	146	6200	682
JL 97-11	6.31	0.43	14.3	18.8
JL 97-12	2.07	155.5	4190	668
JL 97-15	3.46	1.13	32.4	396

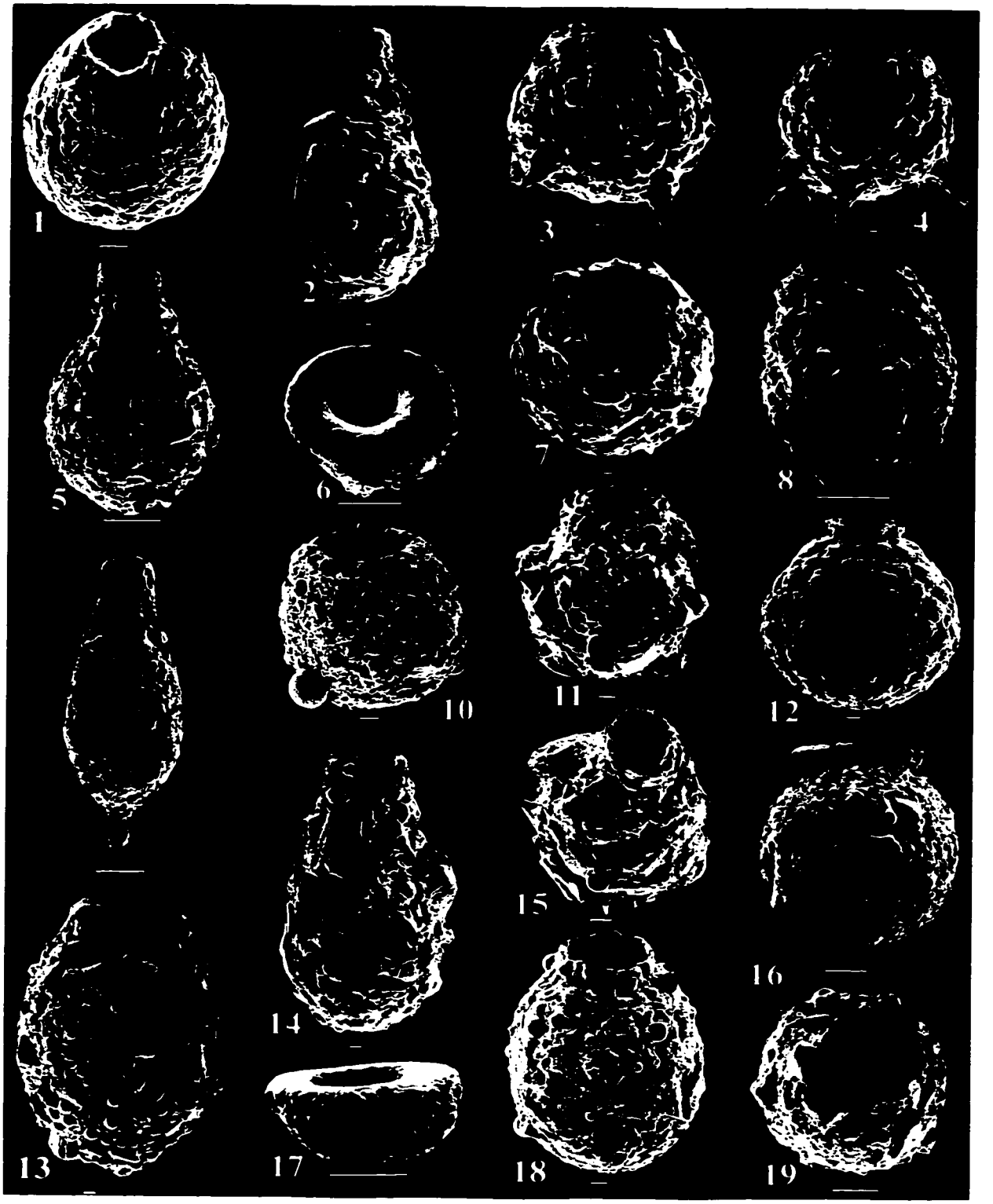
Table 3.

Species/Sample Assemblage	*Arcella* Assemblage (1)	Diverse *Arcella* Assemblage (2)	*Difflugia* Assemblage (3)	*Difflugia protaeiformis* Assemblage (4)	*Lesquerasia* Assemblage (5)	*Centropyxis* Assemblage (6)
Water Depth (m)	1.1	1.1	1.7	4.9	2.4	1.5
Sed/water Interface pH	4.5	3.0	6.7	6.8	6.8	6.4
Sed/water Interface O2	7.2	6.5	7.4	7.4	7.8	8
Sed/water Interface Temperature	22.0	21.5	21.1	19.7	18.6	18
Shannon Diversity Index	0.655	1.079	2.364	2.268	2.386	2.321
Arcella vulgaris	0.691	0.266	0.011	0.015	0.039	0.014
Centropyxis aculeata "aculeata"	0.000	0.038	0.049	0.012	0.055	0.248
Centropyxis aculeata "discoides"	0.001	0.017	0.078	0.035	0.069	0.149
Centropyxix constricta "constricta"	0.000	0.000	0.073	0.047	0.051	0.041
Centropyxis constricta "aerophila"	0.000	0.003	0.020	0.005	0.019	0.017
Cucurbitella triscuspis	0.294	0.583	0.152	0.179	0.269	0.132
Difflugia corona	0.002	0.008	0.025	0.015	0.028	0.003
Difflugia oblonga "glans"	0.001	0.004	0.111	0.098	0.076	0.058
Difflugia oblonga "lithophila"	0.001	0.000	0.139	0.060	0.032	0.014
Difflugia oblonga "oblonga'	0.000	0.015	0.048	0.017	0.016	0.000
Difflugia oblonga "spinosa	0.000	0.000	0.014	0.014	0.009	0.008
Diffligia protaeiformis "acuminata"	0.002	0.006	0.046	0.055	0.066	0.047
Difflugia protaeiformis "amphoralis"	0.000	0.000	0.033	0.229	0.046	0.044
Difflugia protaeiformis "claviformis"	0.000	0.002	0.027	0.086	0.034	0.028
Difflugia urceolata	0.000	0.003	0.052	0.017	0.045	0.036
Lagenodifflugia vas	0.000	0.004	0.004	0.000	0.034	0.094
Lesquerasia spiralis	0.002	0.045	0.072	0.091	0.100	0.058

Photoplate 1

All bars of 10μm length unless mentioned otherwise

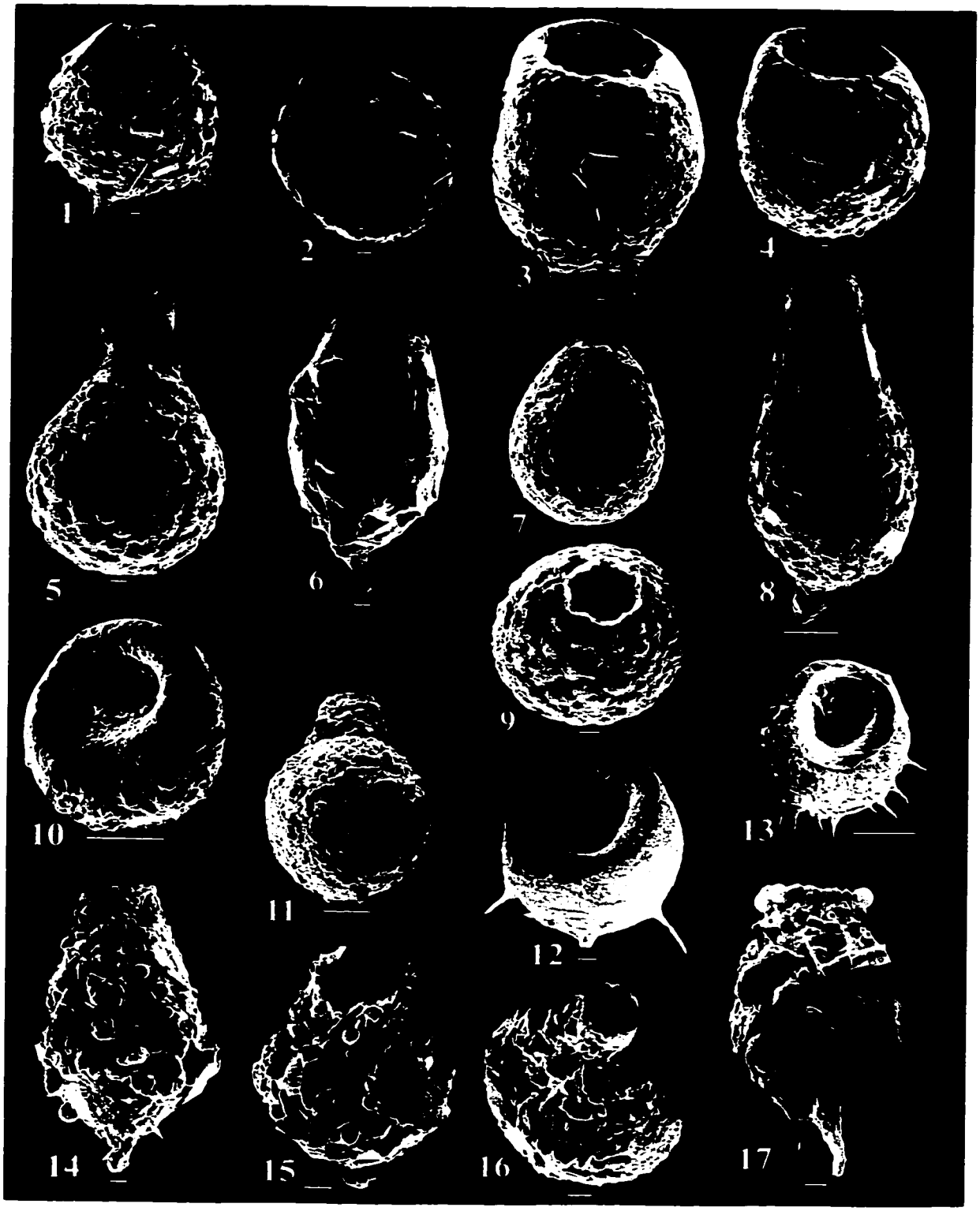
1. Cucurbitella tricuspis (Carter 1856) Medioli, Scott and Abbott, 1987
2. Difflugia oblonga "oblonga" (Ehrenberg 1832) Reinhardt et al. 1998
3. Difflugia corona Wallich 1864
4. Difflugia corona Wallich 1864
5. Difflugia oblonga "oblonga" (Ehrenberg 1832) Reinhardt et al. 1998 (bar length 100μm)
6. Centropyxis aculeata "discoides" (Ehrenberg 1832) Reinhardt et al. 1998 (bar length 100μm)
7. Difflugia corona Wallich 1864
8. Difflugia oblonga "glans" (Ehrenberg 1832) Reinhardt et al. 1998 (bar length 100μm)
9. Lagenodifflugia vas Leidy 1874
10. Difflugia urceolata "urceolata" (Carter 1864) Reinhardt et al. 1998
11. Difflugia oblonga "glans" (Ehrenberg 1832) Reinhardt et al. 1998
12. Difflugia urens Patterson et al. 1985
13. Difflugia oblonga "glans" (Ehrenberg 1832) Reinhardt et al. 1998
14. Difflugia oblonga "bryophila" (Ehrenberg 1832) Reinhardt et al. 1998
15. Difflugia oblonga "linearis" (Ehrenberg 1832) Reinhardt et al. 1998
16. Difflugia urceolata "urceolata" (Carter 1864) Reinhardt et al. 1998
17. Centropyxis aculeata "discoides" (Ehrenberg 1832) Reinhardt et al. 1998 (bar length 100μm)
18. Difflugia urceolata "elongata" (Carter 1864) Reinhardt et al. 1998
19. Difflugia oblonga "glans" (Ehrenberg 1832) Reinhardt et al. 1998 (bar length 100μm)


1
2
3
4
5
6
7
8
10
11
12
13
14
15
16
17
18
19

Photoplate 2

All bars of 10μm length unless mentioned otherwise

1. Difflugia corona Wallich 1864
2. Pontigulasia compressa (Carter 1864) Medioli and Scott 1983
3. Centropyxis constricta "constricta" (Ehrenberg 1843) Reinhardt et al. 1998
4. Centropyxis constricta "aerophila" (Ehrenberg 1843) Reinhardt et al. 1998
5. Lagenodifflugia vas Leidy 1874
6. Difflugia protaeiformis "claviformis" (Lamarck 1816) Reinhardt et al. 1998 (bar length 100μm)
7. Cucurbitella tricuspis (Carter 1856) Medioli, Scott and Abbott, 1987
8. Difflugia protaeiformis "claviformis" (Lamarck 1816) Reinhardt et al. 1998 (bar length 100μm)
9. Cucurbitella tricuspis (Carter 1856) Medioli, Scott and Abbott, 1987
10. Centropyxis aculeata "discoides" (Ehrenberg 1832) Reinhardt et al. 1998 (bar length 100μm)
11. Pontigulasia compressa (Carter 1864) Medioli and Scott 1983 (bar length 100μm)
12. Centropyxis aculeata "aculeata" (Ehrenberg 1832) Reinhardt et al. 1998
13. Centropyxis aculeata "spinosa" (Ehrenberg 1843) Reinhardt et al. 1998 (bar length 100μm)
14. Difflugia protaeiformis "amphoralis" (Lamarck 1816) Reinhardt et al. 1998
15. Difflugia protaeiformis "amphoralis" (Lamarck 1816) Reinhardt et al. 1998
16. Pontigulasia compressa (Carter 1864) Medioli and Scott 1983
17. Difflugia protaeiformis "amphoralis" (Lamarck 1816) Reinhardt et al. 1998


1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

CHAPTER 4. Allochthonous Foraminifera as Evidence of Subaqueous Debris Flows From ODP Site 1033 (Leg 169S), Saanich Inlet, British Columbia

ABSTRACT

The foraminiferal contents of 150 Holocene - latest Pleistocene samples from ODP Site 1033 (Leg 169 S), Saanich Inlet, were analyzed. Sediments of this anoxic fjörd in southern Vancouver Island, British Columbia consist of varved clays inter bedded with slightly coarser massive layers. The 25 species of benthic foraminifera found were predominantly shallow water, calcareous forms, although a few planktic foraminifera and rare arcellaceans as well as deeper water dysoxic benthic forms were also recorded. Most samples contained an impoverished fauna (average of 25 to 30 individuals), but massive layers contained statistically (sign test) higher numbers and diversity of foraminifera than varves. A high proportion (> 50 %) of the foraminiferal fauna was also found to be either damaged or broken. Such a high proportion of broken/damaged foraminifera along with the presence of arcellaceans in the massive layers lend credence to the hypothesis that they were transported from both the coastal regions and shallow well oxygenated parts of the inlet and deposited on the anoxic bottom of Saanich Inlet during seismically induced subaqueous debris flows. The varved sediments also contain broken specimens of foraminifera. Although intact benthic foraminifera within the varves are typically forms capable of withstanding dysoxic conditions and appear to be autochthonous, broken specimens are usually of an allochthonous origin being transported to the deeper anoxic

parts of the inlet during spring freshet along with mineral rich silt. Based on these results the maximum periodicity of slumps generated by small to medium sized earthquakes (minimum $M > 4.5$) at Site 1033 is around 170 years. The high recurrence rate here is because of the relatively steep walls in the narrow part of the fjörd are less stable than other areas of Saanich Inlet.

INTRODUCTION

Seismic activity related to subduction of the Juan de Fuca plate under the North American plate along the Cascadia subduction zone is a major cause for concern in the states of Washington and Oregon and for the province of southern British Columbia (Riddihough and Hyndman, 1976; Hyndman et al. 1996; Clague, 1996). Geophysical models predict that very large earthquakes (magnitude (M) $\geq$ 8) are rare, occurring approximately every 500 - 600 years at the boundary between the plate margins (Rogers, 1988; Atwater et al. 1995; Hyndman, 1995). Smaller but still dangerous earthquakes are more frequent and tend to be centered within the plates (Shedlock and Weaver, 1991; Rogers, 1994). The geophysical models developed to predict the periodicity of earthquakes requires extensive geologic ground testing. The physical effects of Holocene paleoseismic activity in this region have been studied in terms of sea-level changes, isostasy, and records of tsunamis (Long and Shennan, 1994, 1998; Hutchinson et al. 1997; Clague et al. 1999). Research in tidal wetlands, coastal salt marshes and other coastal deposits have proven especially useful in interpreting Holocene paleoseismic events in terms of the resulting geological and geomorphological changes, and environmental damages (Mathewes and Clague, 1994; Nelson et al., 1995, 1996 a, 1996 b,1998; Shennan et al. 1996; Reinhardt et al. 1996). The geologic evidence of Paleoseismicity caused by submarine slides, slumps and debris flows, has also been extensively studied (Middleton and Hampton, 1976; Saxov and Nieuwenhuis, 1980). In particular, Hill et al. (1980)

discussed in detail the mechanism for deposition of thin bedded subaqueous debris flow deposits and sedimentological criteria for identifying them in sediments.

The very well preserved varved sediments of Saanich Inlet on Vancouver Island offer an excellent opportunity to assess the long term history of seismic activity in this region, both in terms of event frequency and intensity. The silty, clayey massive layers interbedded with varves have been demonstrated to be the result of subaqueous debris flows triggered mostly by past earthquakes (Bobrowsky and Clague, 1990; Bobrowsky et al. 1993; Blais, 1992, 1995; Blais-Stevens et al.1997). Blais-Stevens et al. (1997) have estimated that the average occurrence is one debris flow every hundred years with minimum $M > 4.5$ earthquake required to generate such subaqueous gravity flows in Saanich Inlet. This conclusion is compatible both with historical seismicity data and with the rate of liquefaction events observed in Pleistocene lake deposits in Washington State (Sims, 1975). Blais-Stevens (1998) determined that not all massive layers have been formed by seismically induced debris flows though. Some flows have resulted from gravity slumping of sediments along the steep margins of the inlet. For example, bioturbation can destabilize substrates resulting in subaqueous sediment gravity flows (Hecker, 1980).

The long return time for major earthquakes in this region requires detailed analysis of proxy data from the geological record to determine the history of seismic activity. Blais-Stevens et al. (1997) utilized the distribution of allochthonous benthic foraminifera in piston cores from Saanich Inlet to determine the provenance of massive layers. The objective of this study is to similarly use benthic foraminiferal faunas recorded from very

long cores at Ocean Drilling Project (ODP) Site 1033 in Saanich Inlet to determine the applicability of foraminifera to assess the frequency and magnitude of earthquake events during the Holocene.

MATERIAL AND METHODS

Twelve cores (1H to 12H) of varying length were taken at ODP Site 1033 (Hole 1033B) in 238 m of water in southern narrower part of the inlet (Figure 1). Each core was partitioned into 1.5 m sections and numbered from the top. The lowermost section of each core was a shorter core catcher (CC). Details of the standard ODP methods employed for coring and core handling are outlined in Bornhold and Firth et al. (1998) and Westbrook et al. (1994).

Massive layers interbedded with varves occur only in Holocene and youngest Pleistocene sediments (11,668-12,336 ^{14}C yr BP) penetrated by cores 1H to 6H, 0 - 48.1 meters below sea floor (mbsf). Therefore, samples from below this level are not included in this study. The lithology and ^{14}C dates of various core samples are listed in Table 1. Cores were split and analyzed for color using a Minolta spectrometer. The core was also CAT-scanned to reveal details of internal structure and composition, such as the presence of stratified and dispersed sand, ice rafted debris and subtle variations in lithology (Bornhold and Blais-Stevens, 1997).

Sub-sampling for this research was done at the Pacific Geoscience Centre (PGC), Sydney, British Columbia. The sand fraction of 150 samples from cores 1H to 6H was obtained by washing 15 cc core sediment through a 63μm sieve and drying at low

temperature. The resultant sample residues were very small, usually ranging from < 0.001 g to 0.7 g (rarely ≥ 1.0 g) out of 15 cc of core processed. A few processed samples did not have any measurable sand fraction.

All foraminifera in each sample were picked and transferred to slides for subsequent identification. Total number of foraminifera, total number of complete specimens, total number of broken/damaged specimens and number of specimens of various foraminiferal species were recorded for each sample (Table 2). Selected well preserved specimens were digitally photographed at the Carleton University Research Facility for Scanning Electron Microscopy. Identification of foraminifera was primarily based on illustrations in the *Atlas of Common Benthic Foraminiferal Species from Quaternary Shelf Environments of Western Canada* (Patterson et al 1998).

SAANICH INLET AND ITS SEDIMENTARY RECORD

Saanich Inlet is a 26 km long and 0.4 to 7.6 km wide fjörd in southern Vancouver Island. Surface sediments surrounding Saanich Inlet were deposited during the Wisconsinan glaciation and the Holocene (Blyth and Rutter, 1993; Blyth et al. 1993). The inlet is a single basin separated from the oceanic waters of Haro Strait by a bedrock sill at the north end in Satellite Channel (Holland, 1980). The average depth of the inlet is 120 m and its maximum depth is 238 m. The sill at the mouth of the inlet rises to 70 m below the water surface, restricting deep-water circulation. The lower part of the water column, below 70 m, is anoxic (Blais-Stevens et al. 1998). High primary productivity in the inlet in the spring and summer, sluggish estuarine circulation and the presence of abundant

fresh water from Fraser River into Haro Strait, further contribute to the development of bottom water anoxia almost year round in the inlet. The anoxia leads to an absence of most benthic fauna, thus preserving the seasonal record of deposition as fine laminae alternating between an organic-rich plankton fall and terrigenous sediments (Bornhold and Firth et al. 1998). The distribution of the various modern sediment types and sedimentary environments found in this basin along with their associated foraminiferal biofacies (Blais, 1995; Blais-Stevens and Patterson, 1998) has been documented. These data have been invaluable in identifying the source of various foraminiferal species found in the Saanich Inlet cores.

Cores recovered from Hole 1033B can be broadly divided into two sedimentary units. The uppermost approximately 50 m of sediments are a laminated sequence of Holocene olive-gray diatomaceous mud overlying a pre-Holocene sequence of dense, massive to irregularly laminated glaciomarine mud (older than about 12 k yr BP) containing poorly sorted sand lenses and dropstones, as well as graded and contorted sand and silt beds (Bornhold, 1998).

The Holocene sediments are rhythmically-laminated varves of various thickness (5-15 mm thick) as is common in coastal settings at temperate latitudes. Such laminated sediments can provide ultra-high resolution information, providing valuable data on seasonal scale processes as well as intra and inter annual variability (Kemp, 1996). Each laminated sequence consists of "triplets" of thin dark gray terrigenous mud (< 1-2 mm thick), gray terrigenous mud, and light olive laminae of diatom ooze (Bornhold, 1998).

The observed sequence in Saanich Inlet is related to late fall and winter, early spring, and late spring and summer deposition respectively. Unit thickness vary considerably reflecting changes in the amount and seasonal distribution of runoff in nearby watersheds, and in primary productivity (Gross et al., 1963; Sancetta and Calvert, 1988; Bobrowsky and Clague, 1990; Blais-Stevens et al. 1997; Bornhold, 1998).

Sedimentation rates for the varved sediments have been estimated at between 4 and 6 mm per year (Gucluer and Gross, 1964; Blais et al. 1997). According to Bobrowski and Clague (1990), average varve thickness over the past 1,400 years has been 4 mm. Varves are thicker (9 mm) in the northern part of the inlet than in southern (5 mm) part confirming that the primary source of sediments is the Cowichan River watershed at the north end of the inlet (Blais-Stevens et al. 1998).

X-radiography and SEM studies of these varves show that laminated triplets can be consistently subdivided into 12 intra-annual sub-laminae. Inter-annual differences in the number of sub-laminae result from the presence or the absence of ; (1) distinct silt layers, (2) pelletised/diatom "hash" layers, (3) intact, un-pelletised diatom assemblages, (4) monospecific diatom blooms, and (5) exotic diatoms, such as *Thalassiothrix* mats, indicating ocean input (Kemp and Dean, 1998). SEM sediment fabric studies also identify some evidence of micro-benthic bioturbation, probably due to episodes of bottom water renewal resulting from the flow of oxygenated, higher salinity, oceanic water over the sill (Kemp and Dean, 1998).

The laminated sediments are interrupted by thin (< 1-3 mm), light gray clay laminae and thicker massive intervals, a few cm to few tens of cm thick. The clay laminae

appear between winter and summer layers and were deposited during abnormally high spring floods from the Cowichan River. They are more abundant in the northern part of the inlet than southern part, providing further corroboration that the major source of clastic sediments into the inlet is from north and northwest (Blais-Stevens, 1998). During the early Holocene, after initiation of diatomaceous mud deposition, there was a brief period of rapid deposition of gray terrigenous clays with sharp lower contacts. The gray clay bed occurs as a massive layer with a sharp base and grades upward into diatomaceous mud in core 6H-5 between 67 and 123 cm. There is palynological and silicoflagellate evidence suggesting a big terrestrial input of nutrients and fresh water during its deposition (Melissa McQuoid, personal communication 1999). This interval has been interpreted to represent a massive flood event that occurred around 11 k yr BP (Bornhold, 1998).

The massive units are considered to result from episodic debris flows caused by slope failure along the inlet sidewalls. There are more massive layers in the southern part of the inlet (44 at Site 1033) than northern part (22 at Site 1034), where walls are less steep. As might be intuitively inferred, this difference in failure rate is due to the lower stability of fine grained sediments on the steeper slopes (Blais-Stevens et al. 1998).

Massive layers interbedded with varved sediments record all major earthquakes in the region during the past 7 k yr. A diatom marker horizon dated to 1940 AD provides chronological control for the youngest massive layer. Another massive layer dated at 1946 AD, correlates with a large crustal earthquake on central Vancouver Island. This also provides stratigraphic control near the top of the unit. There are also two other layers

that are related to the 1700 AD great earthquake on Cascadia Subduction Zone (Blais-Stevens et al. 1998).

A white volcanic ash layer (1.5-2.0 cm thick) occurs at 37 m depth, and is dated at 7,645 yr BP. This ash layer was deposited following the eruption of Mount Mazama (Crater Lake, Oregon). The lowermost part of this sequence is not well laminated and contains a rich bivalve fauna suggesting a period of 2-3 k yr of well oxygenated waters during the earliest Holocene (Blais-Stevens et al.,1998; Bornhold, 1998). Foraminifera occur in most of the samples from cores 2H to 7H, but the samples below this level are usually barren of foraminiferal faunas. Only 9 of 86 samples examined from cores 8H to 12 H contain foraminifera.

LITHOLOGY AND AGE

The following data are summarized from Bornhold and Firth et al.1998.

Core 1H (0.00-0.6 mbsf); Length cored: 0.6 m; Length recovered: 0.62 m

Age: Holocene

Description: Dark gray soupy diatomaceous mud.

Core 2H (0.6-10.1 mbsf); Length cored: 9.5 m; Length recovered: 9.88 m

Age: Holocene

^{14}C Dates: (2H-7, 28 cm, shell, 1,407-1,715 yr BP)

Description: Dark gray (8Y 3/1) diatomaceous mud. The core is disturbed by gas escape, making accurate assessment of the state of lamination in the top 6 m difficult. The section between 6-10.1 m is less disturbed and laminae are more distinct. Laminae thickness 5-9 mm (average 6 mm) between 7.5-9.0 m and 3-4 mm between 9-9.7 m. Massive layers occur at section 5, 132-150 cm; and section 6, 37-73 cm.

Core 3H (10.1-19.6 mbsf); Length cored: 9.5 m; Length recovered: 10.31 m

Age: Holocene

^{14}C Dates: (3H-5, 144 cm, charcoal, 2,892-3,316 yr BP)

Description: Dark gray (8Y 3/1) diatomaceous mud. Well laminated sediments with intermittent massive layers. Laminae thickness range between 3-10 mm (average 4 mm). A thin (few cm) zone of discontinuous laminae commonly occurs at the base of massive layers. A lamina with abundant plant fragments occurs at section 5, 15 cm. Massive layers occur at section 1, 17-22 cm; section 2, 64-100 cm, 102-109 cm, 119-136 cm; section 3, 78-83 cm, 94-111 cm; section 5, 5-20 cm, 75-126 cm; section 7, 16-20 cm, 37-86 cm.

Core 4H (19.6-29.1 mbsf); Length cored: 9.5 m; Length recovered: 10.24 m

Age: Holocene

Description: Gray to dark gray (8Y 4/1) diatomaceous mud. Well laminated sediments with intermittent massive layers. Laminae thickness range from 1 mm in section 3 to 5 mm in section 5 (average 4 mm). A thin (few cm) zone of discontinuous laminae commonly occurs at the base of massive layers. Massive layers occur at section

1, 0-48 cm; section 2, 5-9 cm, 22-54 cm, 99-101 cm, 126-139 cm; section 3, 72-75 cm; section 4, 59-66 cm; section 6, 92-98 cm; section 7, 73-79 cm; and CC, 11-35 cm.

Core 5H (29.1-38.6 mbsf); Length cored: 9.5 m; Length recovered: 10.11 m

Age: Holocene

^{14}C Dates: (5H-1, 8 cm, charcoal, 6,059-6,389 yr BP; Mazama Ash Bed, 7,645 yr BP)

Description: Gray to dark gray (8Y 4/1) diatomaceous mud. A 2 cm thick gray volcanic ash horizon (Mazama Ash Bed) occurs in section 6, 52-54 cm. The sediments are well laminated in the upper part and discontinuously laminated in the lower part. Laminae are generally of millimeter thickness. Massive layers occur at section 1, 70-85 cm; section 4, 81 to section 5, 18 cm; section 5, 64-72 cm, 113-116 cm, 133-136 cm. Intervals of discontinuous laminae occur in section 1, 78-85 cm; section 2, 69-74 cm, 137-139 cm, section 3, 6-11 cm; section 5, 54-147 cm; section 7, 0-56 cm. Traces of laminae occur in section 7, 56-89 cm.

Core 6H (38.6-48.1 mbsf); Length cored: 9.5 m; Length recovered: 10.25 m

Age: Holocene - Pleistocene

^{14}C Dates: (6H-2, 15 cm, shell, 8,929-9,226 yr BP; 6H-2, 60 cm, shell, 9,078-9,388 yr BP; 6H-2, 90 cm, shell, 9,246-9,474 yr BP; 6H-4, 110 cm, shell, 10,304-10,879 yr BP; 6H-5, 135, shell, 10,952-11,452 yr BP; 6H-5, 141 cm, shell, 11,003-11,643 yr BP; 6H-6, 13 cm, shell, 11,000-11,687 yr BP; 6H-6, 88 cm, shell, 11,668-12,336 yr BP).

Description: Olive gray (10Y 4/1) diatomaceous mud. It is indistinctly laminated from section 1 to section 3, 150 cm and contains traces of laminae from section 4, 0 cm to section 5, 67 cm with massive intervals at section 2, 138 cm to section 3, 17 cm, and section 5, 23-31 cm. The Gray Clay Bed occurs as a massive layer with a sharp base and gradational upper contact to the diatomaceous mud in section 5, 67-123 cm.

RESULTS

One hundred and fifty samples from the upper 48.1 mbsf (cores 1H to 6H) were examined from Hole 1033B, of which 68 samples were from massive layers, and 31 from varves and the rest from distinct or indistinct laminae, breccia or various combinations of different kinds of layers (Table 2). Foraminiferal tests occur both in varves and the massive layers, with typically impoverished foraminiferal assemblages found throughout (Kumar and Patterson, 1998, a b c). On average, only between 25 to 30 specimens per 15 cc were observed in these samples, and a few samples were barren. However, some samples in cores 5H and 6H contained significantly higher numbers of foraminifera (100 - 500 individuals per 15 cc and rarely even higher, see Table 2). The foraminiferal taxa were predominantly benthic, calcareous, shallow water forms. Planktic foraminifera were usually rare, although in a few varves and laminated samples from cores 3H-3, 4H-2, 5H-2, 5H-5 and 5H-7 they occur in significant numbers (10-50 % of the sample assemblage). Rare specimens of arcellaceans, freshwater testate rhizopods, were also observed, but only in the massive layers.

To determine whether there was a statistical difference between the faunas found in the varves and massive layers, the nonparametric statistical sign test (Mendenhall and Beaver, 1994) was conducted on the mean values of total number of foraminifera found in the massive and varved layers (Table 3). The difference between the foraminiferal populations in the massive and varved layers is significant, $p < 0.05$ (calculated value of $p = 0.0352$), with foraminifera being more abundant and diverse in the massive layers than the varves (Figure 2). Species diversity observed in these samples (both massive and varved sediments) was also low, with most samples containing only 5 to 10 species.

A large proportion (> 50 %) of the observed foraminiferal specimens in both massive and varved sediments were damaged or broken (Table 2). In some samples observed from the massive layers all foraminiferal specimens were broken. Few varved sediment samples were dominated by either planktic foraminifera or unbroken specimens of the benthic foraminiferal species *Stainforthia feylingi*.

The most common species of foraminifera observed were *Cribroelphidium excavatum, C. halladense, Lobatula fletcheri, Buccella frigida, B. tenerrima, Nonionella stella and Stainforthia feylingi*. Other less common and rarer species were *Cribroelphidium microgranulosum, C. foraminosum, Homalohedra guntheri, Lagena striatocollis, Bolivinellina pacifica, Fissurina copiosa, F. lucida, Trochammina charlottensis, T. nana, Siphonaperta stalkeri, Lagena striaticollis, Miliammina fusca, Buliminella elegantissima, Nonionella digitata, Astrononion galloway, Rosalina columbiensis*, and *Hyalinonetrion clavatum*. Most of these species are shallow water forms and characterize well oxygenated environments, with the exception of some of the

bolivinid forms and *Stainforthia feylingi* which are known to inhabit dysoxic benthic environments on the British Columbia shelf (Patterson et al. in press).

DISCUSSION

Foraminiferal Assemblages

The foraminiferal fauna of Hole 1033B is predominantly calcareous, and is characterized by the common occurrence of *Lobatula fletcheri, Buccella frigida, Stainforthia feylingi and Cribroelphidium excavatum.* The foraminiferal composition within varves and massive layers does not vary considerably, and correlates well with the *Lobatula fletcheri* Biofacies described from shallower well oxygenated regions of Saanich Inlet by Blais-Stevens and Patterson (1998). This biofacies is characterized by a calcareous fauna, always containing *Lobatula fletcheri,* and is subdivided into the *Stainforthia feylingi* Sub-biofacies and the *Buccella frigida* Sub-biofacies. The *Stainforthia feylingi* Sub-biofacies occurs in deep water, low oxygen environment (basin trough) whereas the *Buccella frigida* Sub-biofacies characterizes shallow water (< 20 m) normal marine environments (bays), and has a patchy distribution probably due to vagaries of water circulation in this restricted basin. At depths of 20-50 m, *Buccella frigida* and *Stainforthia feylingi* occur in approximately equal abundance (Blais-Stevens and Patterson, 1998). Other important taxa identified by Blais-Stevens and Patterson (1998) and found in significant numbers in Hole 1033B include *Cribroelphidium* spp. and *Miliammina fusca. Cribroelphidium* spp. dominate modern assemblages in the inlet at depths of < 5 m. In addition, dissolved *Cribroelphidium* spp. tests, identified by their linings, are found in

most deeper water samples (> 5 m). These linings become more abundant with increasing depth and are thus a significant component of deep water assemblages. *Miliammina fusca* characterizes brackish waters with salinities < 20 ‰ dominates agglutinated foraminiferal assemblages of shallower bays and areas of fresh water discharge.

Foraminiferal composition of the samples from Hole 1033B indicate that sediments of the massive layers were derived from diverse and varied environments ranging from nearshore, shallow, well oxygenated, marine and/or brackish waters to deeper water environments low in dissolved oxygen. For example, the occurrence of *Buccella frigida* and *Stainforthia feylingi* together in several samples indicates that they were derived from deeper waters. Evidence of slumps derived from shoreline sediments is indicated by the presence of *Miliammina fusca* and fresh or brackish water arcellaceans (centropyxids, difflugids and agglutinated spheres). These observations further support the view that massive layers for the most part represent seismically triggered subaqueous debris flows.

In this study, foraminifera were consistently observed both in massive and varved layers from Hole 1033B (see Table 2). This is in sharp contrast to the results of Blais et al. (1997) who observed foraminifera only in the massive layers of piston cores of Saanich Inlet. This discrepancy is difficult to explain. However, the number of foraminiferal specimens found in samples from sections 2H-5, 2H-6 and 3H-2 (6.6 - 13.1 m) are particularly meager, and correspond with the interval examined in the previous study. As the lateral distribution of these low abundance benthic foraminiferal populations in these varves is undoubtedly very uneven, the results of the two studies are probably not as

incompatible as it seems. As indicated by the sign test results, there are statistically higher numbers of foraminifera found in the massive layers indicating that the hypothesis that these massive units are derived by subaqueous debris flows remains valid.

Specimen Damage

A large proportion of foraminiferal specimens was observed to be either broken or otherwise damaged in many samples. Wetmore (1987) found that foraminiferal test strength increases with size and with level of physical environmental stress. Species living in coarse unconsolidated sediment typically have stronger tests than similarly sized individuals from low-energy habitats. These observations suggest a possible explanation for the high proportion of damaged foraminiferal specimens in these samples. Since most living foraminiferal species inhabit low-energy environments in this inlet (Blais and Patterson, 1998), their tests are relatively thin walled. During subaqueous sedimentary flows, tests and sediment particles collide with each other, resulting in significant breakage of tests and provides explanation for the high proportion of damaged specimens in the massive layers.

Damaged specimens were also observed in the varves. The dark silt and clay layers within varves are terrigenous in origin and deposited during fall and spring freshets. This terrigenous sediment is derived from the Cowichan River to the north, Fraser River freshet, Goldstream River in the south and the Fraser River. The broken tests in the varved layers result from the transport of these weaker shelled tests from shallower

depths to the bottom of the inlet during fall and spring freshet (Kumar and Patterson, 1998 b, c).

Oxygen as a Limiting Factor

Some species, notably *Stainforthia feylingi, Nonionella stella,* and *Bolivinellina pacifica* were usually observed intact in the varves (Table 1). These species are known to inhabit dysoxic, deeper water, benthic environments in Santa Barbara basin off southern California and Effingham Inlet, Vancouver Island. (Douglas,1981; Douglas and Heitman, 1979; Bernhard et al. 1997; Patterson et al. In press). *Stainforthia feylingi*, common in Arctic to cold boreal environments (Knudsen and Seidenkrantz, 1994), also characterizes low oxygen environments (Alve, 1990) and in Saanich Inlet it is found abundantly in water depths > 50 m (Blais-Stevens and Patterson, 1998). It has been demonstrated that meiofaunal taxa are less affected by hypoxia than macro and megafauna, and among the meiobenthos hard shelled foraminifera are most resistant to prolonged anoxia (Moodley et al., 1997). Benthic foraminifera thus provide a valuable tool for assessing marine paleo-oxygen conditions (Kaiho, 1994; Sengupta et al. 1996; Bernhard et al. 1997, Patterson et al. in press).

Measured dissolved oxygen levels in the deeper waters in Saanich Inlet generally range from 0.0 mL/L at the bottom to 0.5 mL/L between the 100 - 150 m depth (Herlinveaux, 1962). However, oxygen concentrations at the bottom of the basin increase to 0.5 mL/L in late summer when deeper parts of the basin are flushed (Herlinveaux, 1962; Blais-Stevens and Patterson, 1998). More comprehensive data on the monthly

dissolved oxygen levels in Saanich Inlet between 1953 to 1996 (unpublished data of D. Stucchi, Institute of Ocean Sciences, Figure 3 in Barnhold and Firth et al. (1997) indicate that dissolved oxygen concentration at the bottom of the inlet ranges between 0.0 to 0.2 mL/L. Kaiho (1994) developed a calcareous benthic foraminiferal dissolved-oxygen index. The five oxygenation levels demarcated are; "high oxic", "low oxic", "sub oxic", "dysoxic" and "anoxic" for oxygen levels of 3 - 6, 1.5 - 3, 0.3 - 1.5, 0.1 - 0.3, 0 - 0.1 mL/L respectively. Thus bottom waters in the Saanich Inlet could be classified as "dysoxic" to "anoxic" and specimens of *Stainforthia feylingi, Nonionella stella*, and *Bolivinellina pacifica* found intact in the varves (table 1) are no exception, but prove that these species of benthic foraminifera are capable of inhabiting very low oxygen environments.

Periodicity of Paleoseismic Events

Initially it was not clear whether the massive beds were products of in situ liquefaction of varves, oxygenation of bottom waters and resultant bioturbation of sediments, or sediment gravity flows (Bobrowski and Clague, 1990). Particle-size data indicate that many massive beds are coarser than the bounding varves, supporting an allogenic origin (Bobrowski and Clague, 1990; Blais-Stevens and Patterson,1997). Blais-Stevens and Patterson (1997) gave the following reasons for gravity flow origin of massive beds, (1) basal contacts of massive beds are sharp, and some are clearly erosional, (2) one massive bed has a gravelly base that truncates underlying varves, (3) some massive beds contain varve intraclasts, (4) a zone of brecciated varves marks the base of many massive beds, and (5) most massive beds contain benthic foraminifera, which

implies that the sediment was transported downslope from above the anoxic zone (< 150 m depth). The massive beds are relatively thin (maximum thickness 110 cm) and ascribed to localized submarine sediment gravity flows, rather than large inlet-wide turbidity currents because (1) none of the beds exhibit sedimentary structures and textures typical of a turbidite, (2) there is no normal or inverse grading , (3) about half the beds contain a basal zone of brecciated varves, which were probably formed by shearing at the base of debris flow, and (4) varve intraclasts show no apparent fabric (Blais-Stevens and Patterson,1997).

There are two possible causes for the sediment flows, (1) as sediments build up on submarine slopes, they may exceed the critical angle of repose and slide or flow into deeper water, and (2) sediments may fail when shaken during earthquakes, which would depend on the amount of sediment on the walls of the inlet, the strength of the sediments, the acceleration and period of seismic waves, and the duration of shaking (Blais-Stevens and Patterson,1997). Geotechnical studies on the offshore Vancouver Island sediments by Banks (1997) conclude that earthquake causing slope failures would have to be larger than magnitude 4.5.

Four holes were drilled at Site 1033 (A, B, C and D) and five holes at Site 1034 (A, B, C, D and E). The core details (see Tables 1 and 2 in Barnhold and Firth et al. 1997) and correlation of massive beds at these sites (see Table 5 and 6 in Barnhold and Firth et al. 1997) are given in ODP initial reports on Leg 169 S (Barnhold and Firth et al. 1997). There are 44 and 30 massive beds above the Mazama Ash Bed at Sites 1033 and 1034 respectively. Since all these massive beds occur in at least three or four holes in their

respective sites and can be correlated well, they are considered to be of seismic origin (Blais-Stecvens et al. 1998). The ^{14}C dates above the Mazama Ash Bed provided a fairly good time framework in the absence of varve count data. The number of massive beds was identified between the two known ^{14}C dates, providing a mean value for the occurrence of massive beds for that duration (Table 4). The results show quite a variation, the average time for Site 1033 is one earthquake in every 170.15 years, and for Site 1034 this value is 276.14 years.

Sims (1975) calculated an average of 129 years between seismic events for Puget Lowlands, Washington Sate. In case of Saanich Inlet, the average is 116 for the last 1,500 years (Blais-Stevens and Patterson, 1997). Based on historical seismic records and the rate of liquefaction events seen in the Pleistocene lake deposits in Washington State, an average of one earthquake every 100 years has been postulated (Sims, 1975; Blais, 1992; Blais-Stevens and Patterson,1997). Based on the other evidence from the region, larger earthquakes (> 8 magnitude, of subduction origin) have a return period of ~600 years (Barnhold and Firth et al. 1997). Considering these values on the periodicity of earthquake events in this region, new data from Sites 1033 and 1034 in the Saanich Inlet are not only compatible, but also provide some clue on the relative magnitude of the of the past earthquakes. The results indicate that earthquakes of lesser or higher magnitude (M>4 or 5) were recorded at Site 1033 (170 years periodicity), which is narrower and steeper part of the Saanich Inlet where sediments are less stable. Earthquakes of only higher magnitude (M>8 or 9) were recorded at the Site 1034 (276

years periodicity), which is wider and less steep, thus would require stronger earthquake to generate a massive bed.

CONCLUSIONS

The foraminiferal fauna of the ODP Hole 1033B was impoverished with low absolute numbers and low species diversity in most of the samples. Most of the species were derived from shallow, well oxygenated coastal environments although in situ species occurring in the deeper lower oxygen environments were also found.

Benthic foraminifera are useful in distinguishing sediments of massive layers which originated by subaqueous sediment flows from annually deposited varved layers in an anoxic basin. The two distinguishing characters are: (1). massive layers contain larger numbers and relatively higher diversity of benthic foraminifera than varves, and (2). varves contain intact, autochthonous specimens of deeper water dysoxic foraminiferal species in addition to some allochthonous forms, whereas massive layers contain only allochthonous foraminiferal fauna derived from different environments of the inlet.

A large proportion of the foraminiferal specimens was either broken or damaged. This is mainly due to collision of thin walled tests with sediment particles during subaqueous sediment flows. Transport of these forms from shallower environments to the deeper parts of the inlet during spring freshets also causes breakage.

Occurrence of autochthonous intact specimens of *Stainforthia feylingi, Nonionella stella,* and *Bolivinellina pacifica* in the varves deposited in "dysoxic" to "anoxic"

environments indicate that these species of benthic foraminifera are capable of inhabiting even in very low oxygen environments.

The estimated periodicity of small or large earthquakes (M>4 or 5) average to be every 170 years were recorded at narrower and steeper Site 1033, and only larger earthquakes (M>8 or 9) estimated to occur every 280 years were recorded at wider and less steep at Site 1034.

ACKNOWLEDGMENTS

This research was supported by a NSERC research grant and NSERC collaborative special grant to RTP. We wish to thank Dr. John Logan of the Department of Psychology, Carleton University for assisting with non parametric statistical analysis.

REFERENCES

Atwater, B. F., Nelson, A. R., Clague, J. J. et al., 1995. Summary of coastal geologic evidence for the past great earthquakes at the Cascadia subduction zone. Earthquake Spectra, 11: pp.1-18.

Alve, E. 1990., Variations in estuarine foraminiferal assemblages with diminishing oxygen conditions in Drammensfjord, SE Norway: Paleoecology, Biostratigraphy, Paleoceanography and Taxonomy of Agglutinated Foraminifera, NATO Series, C, Mathematical and Physical Sciences, v. 327: pp. 661-694.

Banks, S. 1997., Geotechnical analysis of two sites offshore Vancouver Island, British Columbia: establishing the frequency of earthquakes since the last ice age through 100 % borehole recovery. B.Sc. thesis, Technical University, Halifax, N. S.

Bernhard, J. M., Sen Gupta, B. K., & Borne, P. F., 1997. Benthic foraminiferal proxy to estimate dysoxic bottom-water oxygen concentrations: Santa Barbara Basin, U.S. Pacific continental margin. Journal of Foraminiferal Research, v. 27(4): pp. 301-310.

Blais, A. 1992. Holocene sediments from Saanich Inlet, British Columbia and their neotectonic significance. In, Current Research, part A. Geological Survey of Canada, Paper 92-1A, pp.195-198.

Blais, A., 1995. Foraminiferal biofacies and Holocene sediments from Saanich Inlet, British Columbia: implications for environmental and neotectonic research. Ph.D. thesis, Carleton University, Ottawa, Ontario, Canada.

Blais-Stevens, A. 1998. Holocene spring flood deposits in Saanich Inlet, BC: a paleoclimatic record ? Geological Association of Canada/Mineralogical Association of Canada, 1998 Meeting, Quebec City. (Abstract).

Blais-Stevens, A., Clague, J. J., Bobrowsky, P. T.,& Patterson, R. T. 1997. Late Holocene sedimentation in Saanich Inlet, British Columbia, and its paleoseismic implications. Canadian Journal of Earth Sciences, v. 34(10): pp.1345-1357.

Blais-Stevens, A. & Patterson, R. T., 1998. Environmental indicator potential of foraminifera from Saanich Inlet, Vancouver Island, British Columbia, Canada. Journal of Foraminiferal Research, v. 28(3): pp. 201-219.

Blais-Stevens, A., Clague, J. J. & Bobrowsky, P. T. 1998. Holocene sedimentation in Saanich Inlet, B. C.: Implications for prehistoric earthquake history. Geological Association of Canada/Mineralogical Association of Canada, 1998 Meeting, Quebec City. (Abstract).

Blaise, B., Clague, J. J., and Mathewes, R. W. 1990. Time of maximum Late Wisconsin glaciation, west coast of Canada. Quaternary Research, v. 34: 282-295.

Blyth, H. E. & Rutter, N. W., 1993. Surficial geology of the Sydney area. Ministry of Energy, Mines and Petroleum Resources, BC., Open file map 1993-24, NTS 92B/11.

Blyth, H. E., Rutter, N. W., & Sankeralli, L. M., 1993. Surficial geology of the Shawnigan Lake area. Ministry of Energy, Mines and Petroleum Resources, BC. Open file map 1993-26, NTS 92B/12.

Bobrowsky, P. T. & Clague, J. J., 1990. Holocene sediments from Saanich Inlet, British Columbia, and their neotectonic implications. In Current Research, part E. Geological Survey of Canada Paper 90-1E, pp. 251-256.

Bobrowsky, P. T., Clague, J. J. & Blais, A. 1993. Late Holocene earthquakes: the geological record from Saanich Inlet, southern Strait of Georgia. Proceedings, Conference on Large Earthquakes and Active Faults in the Puget Sound Region. University of Washington, Seattle, Washington. May 13-14, 1993.

Bornhold, B. D. 1998. The Ocean Drilling Program Leg 169 S in Saanich Inlet, British Columbia- Overview. Geological Association of Canada/ Mineralogical Association of Canada Annual Meeting, Quebec City. (Abstract).

Bornhold, B. D. & Blais-Stevens, A. 1997. Core Baselines. In, Ultra-high resolution climatic, oceanographic, biological and geochemical records in Saanich Inlet, British Columbia, ODP Leg 169 S. 1st Annual report (M. J. Whiticar), Centre for Earth & Ocean Research, University of Victoria, pp. 6-9.

Bornhold, B., Firth, J. V. et al. 1998. Proc. ODP. Init. Repts., 169S: College Station, Texas (Ocean Drilling Program), pp. 1-138.

Clague, J. J., 1996. Paleoseismology and seismic hazards, southwestern British Columbia. Geological Survey of Canada, Bulletin 494, pp. 20-34.

Clague, J. J., Hutchinson, I., Mathewes, R. W. and Patterson, R. T., 1999. Evidence for Late Holocene tsunamis at Catala Lake, British Columbia. Journal of Coastal Research, v.15, pp. 45-60.

Douglas, R. G., 1981. Paleoecology of continental margin basins: A modern case history from the borderland of Southern California, in Douglas, R. G., Colburn, I. P. & Grosline, D. S. (eds.), Depositional System of Active Continental Margin Basins: Short Course Notes: SEPM Pacific Section, San Francisco, pp. 121-156.

Douglas, R. G. & Heitman, H. L., Slope and basin benthic foraminifera of the California borderland: SEPM Special Publication, v. 27, pp. 231-246.

Gross, M. G., Gucluer, S. M., Creager, J. S. and Dawson, W. A., 1963. Varved marine sediments in a stagnant fjord. Science, v. 141, pp. 918-919.

Gucluer, S. M. & Gross, M. G. 1963. Recent marine sediments in Saanich Inlet, a stagnant marine basin. Limnology and Oceanography, v. 9, pp. 359-376.

Hecker, B. 1980. Possible benthic fauna and slope instability relationships. In: Saxov, S and Nieuwenhuis, J. K. (Editors), Marine slides and other mass movements. NATO Scientific Affairs Division. Plenum Press, pp. 335-347.

Hill, P. R., Aksu, A. E. and Piper, D. J. W. 1980. The deposition of thin bedded subaqueous debris flow deposits. In: Saxov, S and Nieuwenhuis, J. K. (Editors), Marine slides and other mass movements. NATO Scientific Affairs Division. Plenum Press, pp. 273-287.

Holland, S. S. 1980. Landforms of British Columbia, a physiographic outline. British Columbia Ministry of Energy, Mines and Petroleum Resources, Bulletin 48, p.138.

Hutchinson, I., Clague, J. J. & Mathews, R. W. 1997. Reconstructing the tsunami record on an emerging coast: a case study of Kanim Lake, Vancouver Island, British Columbia, Canada. Journal of Coastal Research, v. 13(2), pp. 545-553.

Hyndman, R. D., 1995. Giant earthquakes of the Pacific Northwest. Scientific American, v. 273(6), pp. 68-75.

Hyndman, R. D., Rogers, G. C. et al. 1996. Giant earthquakes beneath Canada's west coast. Geoscience Canada, v. 23(2), pp. 63-72.

Kaiho, K. 1994. Benthic foraminiferal dissolved-oxygen index and dissolved-oxygen levels in the modern ocean. Geology, v. 22, pp. 719-722.

Kemp, A. E. S., 1996. Palaeoclimatology and palaeoceanography from laminated sediments. Geol. Soc. Spe. Publ. No. 116. The Geological Society, London. P. 258.

Kemp, A. E. S. & Dean, 1998. Ultra-high resolution paleoclimatology and paleoceanography from Holocene laminated sediments: preliminary results from Saanich Inlet, ODP, Leg 169 S. Geological Association of Canada/ Mineralogical Association of Canada, Annual Meeting, Quebec City. (Abstract).

Knudsen, K. L. & Seidenkrantz, M. S., 1994. Stainforthia feylingi: New species from Arctic to Sub-arctic environments, previously recorded as Fursenkoina schreibersiana (Czjzek): Contributions from the Cushman Foundation of Foraminiferal Research, Spe. Publ. No. 32, pp. 5-13.

Kumar, A. & Patterson, R. T. 1998 A. Allochthonous foraminifera as evidence of subaqueous debris flows from ODP site 1033 B (Leg 169 S), Saanich Inlet, British Columbia. Geological Association of Canada/Mineralogical Association of Canada Annual Meeting, Quebec City. (Abstract).

Kumar, A. & Patterson, R. T. 1998 B. Foraminiferal Analysis. In, Whiticar, M. et al., Ultra-high resolution climatic, oceanographic, biological and geochemical records in Saanich Inlet, British Columbia, ODP Leg 169 S. 2nd Year Annual Report, Centre for Earth and Ocean Research, University of Victoria., pp. 31-32.

Kumar, A. & Patterson, R. T. 1998 C. Foraminiferal analysis of the cores from ODP site 1033 B (Leg 169 S), Saanich Inlet, British Columbia: evidence for subaqueous debris flows. Geol. Soc. America Annual Meeting, Toronto. (Abstract).

Long, A. J. & Shennan, I., 1994. Sea-level changes in Washington and Oregon and the "Earthquake Deformation Cycle". Journal of Coastal Research, v. 10, pp. 825-838.

Long, A. J. & Shennan, I., 1998. Models of rapid relative sea-level change in Washington and Oregon, USA. The Holocene, v. 8(2), pp. 129-142.

Mathewes, R. W. & Clague, J. J., 1994. Detection of large prehistoric earthquakes in the Pacific northwest by microfossil analysis. Science, v. 264, pp. 688-691.

Mendenhall, W. & Beaver, R. J. Introduction to Probability and Statistics. Duxbury Press, Belmont, California. 704 P. (9th edition).

Middleton, G. V. and Hampton, M. A., 1976. Subaqueous sediment transport and deposition by sediment gravity flows. In: Stanley, D. J. and Swift, D. J. P. (editors),

Marine Sediment Transport and Environmental Management. John Wiley & Sons, pp.197-218.

Moodley, L., van der Zwan, G. J., Herman, P. M. J., Kempers, L. and van Breugel, P. 1997. Differential response to benthic meiofauna to anoxia with special reference to Foraminifera (Protista: Sarcodina). Marine Ecology Progress series, v. 158, pp. 151-163.

Nelson, A. R., Atwater, B. F. et al., 1995. Radiocarbon evidence for extensive plate-boundary rupture about 300 years ago at the Cascadia subduction zone. Nature, v. 378, pp. 371-375.

Nelson, A. R., Shennan, I. & Long, A. J., 1996 A. Identifying coseismic subsidence in tidal-wetland stratigraphic sequences at the Cascadia subduction zone of western North America. Journal of Geophysical Research, v. 101, pp. 6115-6135.

Nelson, A. R., Jennings, A. E. & Kashima, K., 1996 B. An earthquake derived from stratigraphic and microfossil evidence of relative sea-level change at Coos Bay, southern coastal Oregon. Geological Society of America Bulletin, v. 108(2), pp. 141-154.

Nelson, A. R., Ota, Y., Umitsu, M., Kashima, K. & Matsushima, Y., 1998. Seismic and hydrodynamic control of rapid late-Holocene sea-level rises in southern coastal Oregon, USA ?. The Holocene, v. 8(3), pp. 287-299.

Patterson, R. T. & Fishbein, E., 1989. Re-examination of the statistical methods used to determine number of point counts needed for micropaleontological quantitative research. Journal of Paleontology, v. 63, pp. 245-248.

Patterson, R. T., Guilbault, J. P. & Thomson, R. E., In Press. Oxygen level control on foraminiferal assemblage distribution in Effingham Inlet, Vancouver Island, British Columbia. Journal of Foraminiferal research.

Patterson, R. T., Burbridge, S. M. and Luternauer, J. L. 1998. Atlas of Common Benthic Foraminiferal Species for Quaternary Shelf Environments of Western Canada. Geological Survey of Canada Bulletin 503, 91 P.

Reinhardt, E. G., Easton, N. A. and Patterson, R. T., 1996. Foraminiferal evidence of Late Holocene sea-level change and Amerindian site distribution at Montague Harbour, British Columbia. Geographie physique et Quaternaire. V. 50, pp. 35-46.

Riddihough, R. P. & Hyndman, R. W., 1976. Canada's active western margin-the case for subduction. Geoscience Canada, v. 3, pp. 269-278.

Rogers, G. C., 1988. An assessment of the megathurst earthquake potential of the Cascadia subduction zone. Canadian Journal of Earth Science,. V. 25, pp. 844-852.

Rogers, G. C., 1994. Earthquakes in Vancouver. In: Geology and geological hazards of the Vancouver region, southwestern British Columbia. Edited by J. W. H. Monger. Geological Survey of Canada, Bulletin 481, pp. 221-229.

Sancetta, C. & Calvert, S. E. 1988. The annual cycle of sedimentation in Saanich Inlet, British Columbia: implications for the interpretation of diatom fossil assemblages. Deep-Sea Research, v. 35(1), pp. 71-90.

Saxov, S. and Nieuwenhuis, J. K., 1980. Marine slides and other mass movements. NATO Scientific Affairs Division. Plenum Press, p. 353.

Sen Gupta, B. K., Platon, E., Bernhard, J. M. & Aharon, P., 1997. Foraminiferal colonization of hydrocarbon-seep bacterial mats and underlying sediment, Gulf of Mexico slope. Journal of Foraminiferal Research, v. 27(4), pp. 292-300.

Shedlock, K. M. & Weaver, C. S., 1991. Program for earthquake hazards assessment in the Pacific Northwest. United States Geological Survey, Circular 1067.

Shennan, I., Long, A. J. et al. 1996. Tidal marsh stratigraphy, sea-level change and large earthquakes, I: A 5000 year record in Washington, USA. Quaternary Science Reviews, v. 15, pp. 1023-1059.

Sims, J. D. 1975. Determining earthquake intervals from deformational structures in young lacustrine sediments. Tectonophysics, 29, pp. 141-152.

Westbrook, G. K., Carson, B., Musgrave, R. J. et al. 1994. Proc. ODP, Init. Repts., 146 (Pt. 1): College Station, TX (Ocean Drilling Program).

Wetmore, L. K., 1987. Correlation between test strength, morphology and habitat in some benthic foraminifera from the coast of Washington. Journal of Foraminiferal Research, v. 17, pp. 1-13.

FIGURES

TABLES

Figure 1. Location map of Saanich Inlet and ODP Site 1033

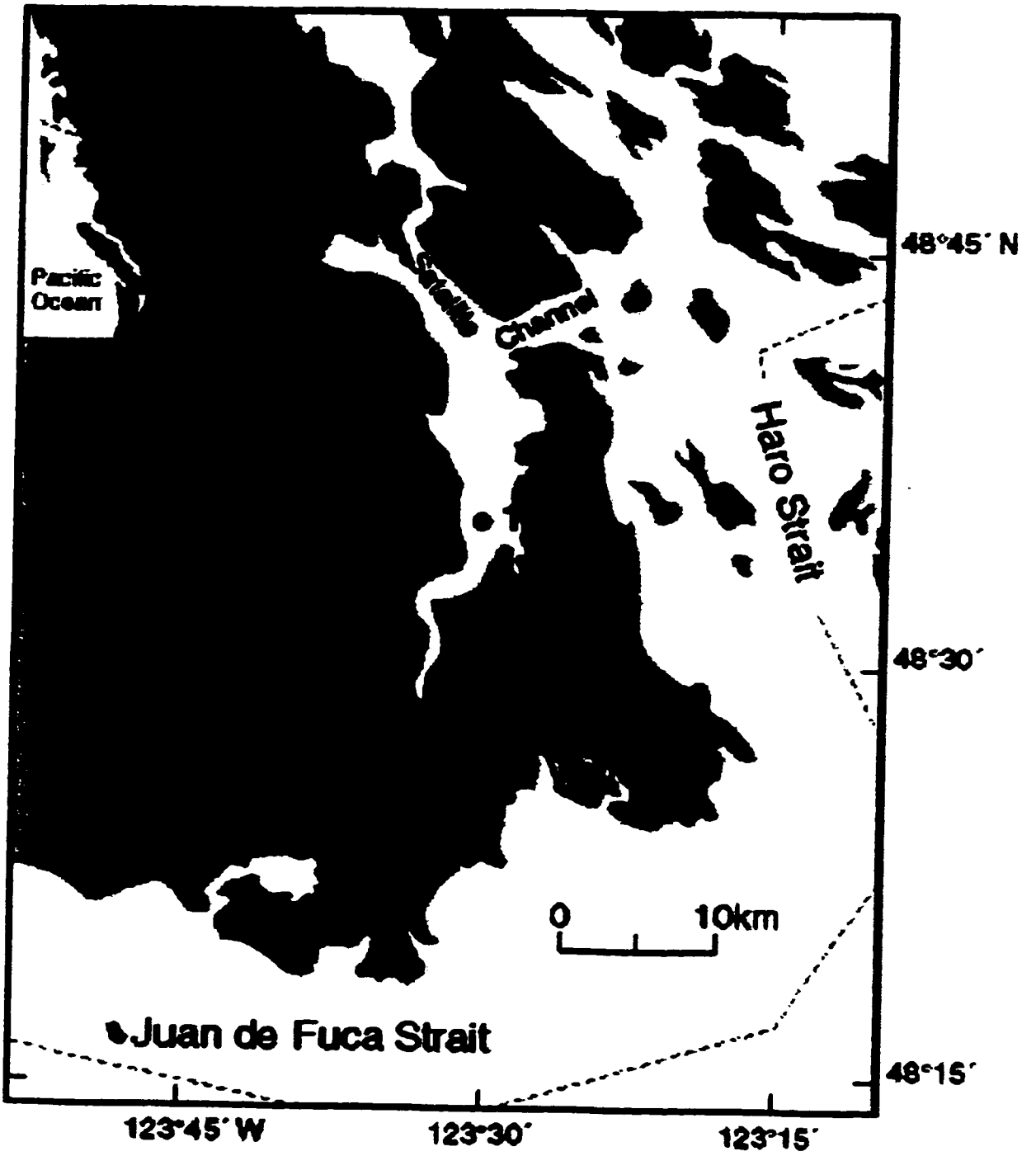


Figure 2. Numerical abundance of benthic foraminifera in massive beds and varves

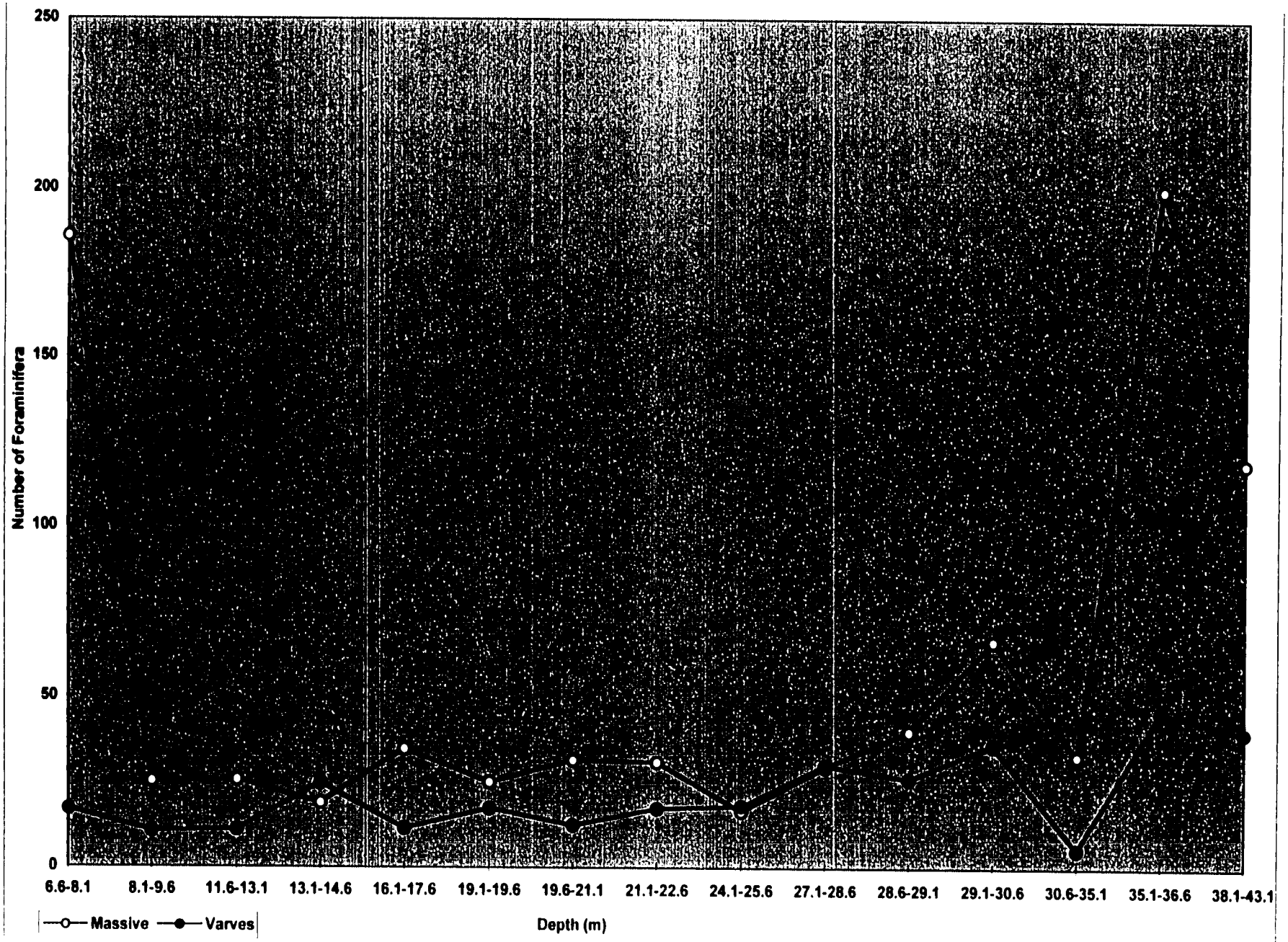


Table 1: Stratigraphy, lithology and carbon dates of studied core at site 1033B (Bornhold and Firth et al. 1998)

Core No.	Depth (mbsf)	Lithology	Radiocarbon dates (^{14}C)	Age
1 H	0.0-0.6	Dark gray diatomaceous mud (soupy)	-	Holocene
2H	0.6-10.1	Dark gray diatomaceous mud (top part not well laminated)	1,407-1,715 yr BP (2H-7, 28 cm)	Holocene
3H	10.1-19.6	Dark gray diatomaceous mud (well laminated with massive beds)	2,892-3,316 yr BP (3H-5, 144 cm)	Holocene
4H	19.6-29.1	Gray diatomaceous mud (well laminated with massive beds)	-	Holocene
5H	29.1-38.6	Gray diatomaceous mud (Laminated with Mazama Ash Bed)	6,059-6,389 yr BP (5H-1, 8 cm) MAB: 7,645 yr BP	Holocene
6H	38.6-48.1	Olive gray diatomaceous mud (Indistinctly laminated with massive beds with Gray Clay Bed)	8,929-9,226 yr BP (6H-2, 15 cm) 9,078-9,388 yr BP (6H-2, 60 cm) 9,246-9,474 yr BP (6H-2, 90 cm) 10,304-10,879 yr BP (6H-4, 110 cm) 10,952-11,452 yr BP (6H-5, 135 cm) 11,003-11,643 yr BP (6H-5, 141 cm) 11,000-11,687 yr BP (6H-6, 13 cm) 11,668-12,336 yr BP (6H-6, 88 cm)	Holocene Pleistocene

Table 3. Mean of total number of foraminifera in massive beds and varves

Core No.	Depth (m)	Mean of Total Number of Forams (Massive Beds / Varves)
2H5	6.6-8.1	186 / 17
2H6	8.1-9.6	25 / 10.5
3H2	11.6-13.1	25.42 / 11
3H3	13.1-14.6	18.8 / 24.66
3H5	16.1-17.6	34.62 / 11.33
3H7	19.1-19.6	24.87 / 17.33
4H1	19.6-21.1	31.44 / 12.33
4H2	21.1-22.6	30.8 / 17.2
4H4	24.1-25.6	16.5 / 18
4H6	27.1-28.6	29.5 / 30
4H7	28.6-29.1	40 / 26
5H1	29.1-30.6	66.5 / 36
5H2-5H4	30.6-35.1	32.87 / 5.5
5H5	35.1-36.6	390.14 / 45.83
5H7-6H3	38.1-43.1	119 / 39.83

Table 4. Estimation of periodicity of earthquakes in Holes 1033B and 1034B

Core Section Interval (cm)	Calibrated ^{14}C date yr BP	Duration Between ^{14C} Dates	Number of Massive Beds	Mean Value
Hole: 1033B				
2H-7, 28	1,407 to 1,715 median=1561	1, 561 yr	9	1561/9=173.44 yr
3H-5,144	2,892 to 3,316 median=3,104	3,104-1,561 =1543 yr	10	1543/10=154.3 yr
5H-1,8	6,059 to 6,389 median=6,224	6,224-3,104 =3120 yr	16	3120/16=195 yr
Mazama Ash	7,645	7,645-6,224 =1421 yr	9	1421/9=157.85 yr
				Average=170.15 yr
Hole: 1034B				
2H-4,118	868 to 1,199 median=1,034	1,034 yr	4	1,034/4=285.5 yr
3H-2,113	1,631 to 1,923 median=1,777	1,777-1034 =744 yr	7	744/7=106.28 yr
4H-2,52	2,781 to 3,156 median=2,973	2,973-1,777 =1,196 yr	5	1,196/5=239.2 yr
4H-4,56	4,554 to 4,977 median=4,766	4,766-2,973 =1,792 yr	4	1,792/4=448 yr
6H-4,3	6,303 to 6,632 median=6,468	6,498-4,766 =1,702 yr	6	1,702/6=283.66 yr
Mazama Ash	7,645	7,645-6,468 =1,177 yr	4	1,177/4=294.25 yr
				Average=276.14 yr

CHAPTER 5. Foraminifera as Proxy for Paleoceanographic and Paleoclimatic Record of ~15 k yr, BP, Saanich Inlet, Southern Vancouver Island, B.C., Canada

ABSTRACT

Benthic foraminifera from sand fraction samples (Holocene - latest Pleistocene) of ODP holes 1033B and 1034B (Leg 169 S), Saanich Inlet, were studied. This inlet is an anoxic fjörd in southern Vancouver Island. The sediments are varved and interbedded with slightly coarser massive layers of variable thickness. The foraminifera found in this deep water environment were predominantly shallow water, benthic, calcareous forms. A few planktic foraminifera and rare arcellaceans were also found. Most samples contained an impoverished fauna, but massive layers usually contain higher numbers and diversity of foraminifera than varves. The foraminiferal counts were very low (average of 25 to 30 specimens), however, a few samples contained >100 specimens, and rare samples contained even >500 specimens of foraminifera. Q-mode cluster analysis on the 58 samples having statistically significant numbers of foraminifera identified five distinct biofacies. These biofacies are controlled primarily by paleoclimatic change from the Pleistocene to the Holocene when glacial conditions changed to warmer interglacial environments. Sea level rise and fall, associated paleo-circulation patterns and development of suboxic/anoxic conditions in the bottom of the inlet during Holocene also had a major control over the distribution of the biofacies.

INTRODUCTION

The Ocean Drilling Program (ODP) drilling ship JOIDES Resolution drilled at two Sites 1033 and 1034 in Saanich Inlet during Leg 169S to southern Vancouver Island in August,1996 (Figure 1). Hole 1033B was 105 m thick and Hole 1034B was 118 m thick. The cores provided a continuous sediment record of period from the last glaciation (~15 k yr BP) through the late Holocene (Whiticar et al. 1997). Inlets and fjörds are useful in paleoceanographic research because in many cases only strong oceanographic events are felt and recorded in the sedimentary records (Thomson, 1981). This characteristic makes paleoceanographic interpretation easier for researchers as the noise of background productivity is filtered out (Patterson et al. in press). Saanich Inlet was selected for coring because the bottom of this inlet is dysoxic to anoxic, resulting in very few benthic organisms. Thus undisturbed layers of sediments recorded climatic events as subtle as seasonal variations and environmental history of southern Vancouver Island through most of the Holocene.

The derived sedimentological and microfossil (pollen, diatom and foraminifera) evidence provides a good proxy record of a number of phenomena including paleoceanography, sea-level changes, climatic oscillations and catastrophic events like earthquakes, floods and tsunamis.

The Quaternary stratigraphy, environmental and climatic history of southern British Columbia has previously been discussed by Blaise et al. (1990), Clague (1994), Clague and Mathewes (1989), Huntley et al.(1998), and Huntley (1999). During the Quaternary there is evidence of several glacier-dammed lakes and subsequent catastrophic

flooding due to breakage of ice dams (Clague and Mathewes, 1996; Cowan et al. 1996). The other significant Quaternary events recorded in this region are the fluctuations in the sea-level in response to climatic changes and isostatic rebound during interglacial periods (Friele and Hutchinson, 1993; Hutchinson et al. 1997; Luternauer et al. 1989; Reinhardt et al. 1996).

The distribution of modern benthic foraminifera on the Pacific coast of North America, from Oregon to Alaska was summarized by Culver and Buzas (1985). Their publication provides maps of 138 most commonly recorded species in this region. Benthic foraminifera have previously been used for a variety of late Quaternary paleo-oceanographic studies on the British Columbia coastal regions e.g. (Patterson, 1993; Patterson and Cameron, 1991; Patterson et al. 1995, in press; Guilbault et al. 1997). Blais-Stevens and Patterson (1998) identified five benthic foraminiferal biofacies from recent sediments representing distinct sub-environments with in Saanich Inlet. Late Quaternary abrupt climatic events like the Younger Dryas event were identified on the British Columbia coast using benthic foraminiferal evidence (Mathewes et al. 1993; Patterson et al. 1995). The objectives of this paper are to identify post-glacial climatic signals and reconstruct the paleoceanographic history of this inlet and surrounding water masses.

SAANICH INLET AND ITS SEDIMENTS

Saanich Inlet is a 26 km long and 0.4 to 7.6 km wide anoxic fjörd in southern Vancouver Island. Two distinct sedimentary units were identified in the cores at sites

1033 and 1034 in the inlet. The late Pleistocene deeper (>70 meters below sea floor (mbsf) at Site 1034 and >50 mbsf at Site 1033) sediments are oxic, non laminated, rich in terrestrial organic matter, and are of glacio-marine origin. The overlying Holocene sediments are anoxic, laminated, hemipelagic sediments which are dominated by moderately high marine primary productivity, largely marine phytoplankton (Whiticar et al., 1998). The pre-Holocene oxic depositional environment supported benthic communities that bioturbated the sediments and destroyed the record of any sediment laminations, whereas Holocene sediments are well laminated due to anaerobic conditions that precluded infauna and bioturbation (Whiticar et al., 1998).

Surface sediments surrounding Saanich Inlet were deposited during the Wisconsinan glaciation and subsequent Holocene deglaciation (Blyth and Rutter, 1993; Blyth et al. 1993; Clague, 1994; Huntley et al. 1998; Huntley, 1999). The inlet is a single basin separated from the oceanic waters of Haro Strait by a bedrock sill at the north end in Satellite Channel (Holland, 1980). The average depth of the inlet is 120 m and its maximum depth is 238 m. The sill at the mouth of the inlet rises to 70 m below the water surface, restricting deep-water circulation. The lower part of the water column, below 70 m is dysoxic to anoxic (Blais-Stevens et al. 1998). High primary productivity in the inlet during spring and summer, sluggish estuarine circulation and the presence of abundant fresh water from Fraser River in Haro Strait, contributes to the development of bottom water anoxia almost year round in the inlet. This anoxia leads to an almost complete absence of benthic fauna, thus preserving the seasonal record of deposition as fine laminae alternating between plankton fall and terrigenous sediments (Bornhold and Firth et

al.1998). The distribution of the various modern sediment types and sedimentary environments in this basin along with their associated foraminiferal biofacies have been documented by Blais (1995) and Blais-Stevens and Patterson, (1998). These data have been invaluable in identifying the source of various foraminiferal species found in the Saanich Inlet cores.

Cores recovered from these sites can be broadly divided into two sedimentary units. The upper section at each site is a laminated sequence of Holocene olive-gray diatomaceous mud overlying a sequence of dense, massive to irregularly laminated glacio-marine mud (older than about 12 k yr BP) containing poorly sorted sand lenses and dropstones, as well as graded and contorted sand and silt beds (Bornhold, 1998).

The Holocene sediments are rhythmically laminated (varves), and of various thickness (5-15 mm thick) as is fairly common in coastal settings at temperate latitudes. Such laminated sediments can provide ultra-high resolution information, providing valuable data on seasonal scale processes as well as intra and interannual variability (Kemp, 1996). Each laminated sequence consists of "triplets" of thin dark gray terrigenous mud (1-2 mm thick), gray terrigenous mud, and light olive laminae of diatom ooze (Bornhold, 1998).

The observed sequence in Saanich Inlet is related to late fall and winter, early spring, and late spring and summer deposition respectively. Unit thickness vary considerably reflecting changes in the amount and seasonal distribution of runoff in nearby watersheds, and in primary productivity (Gross et al., 1963; Sancetta and Calvert, 1988; Bobrowsky and Clague, 1990; Blais-Stevens et al. 1997; Bornhold, 1998).

Sedimentation rates for the varved sediments have been estimated at between 4 and 6 mm per year (Gucluer and Gross, 1964; Blais-Stevens et al. 1997). According to Bobrowski and Clague (1990), average varve thickness over the past 1,400 years has been 4 mm. Varves are thicker (9 mm) in the northern part of the inlet than in southern (5 mm) part confirming that the primary source of sediments is from the Cowichan River watershed at the north end of the inlet (Blais-Stevens et al. 1998).

X-radiography and SEM studies of these varves show that laminated triplets can be consistently subdivided into 12 intra-annual sub-laminae. Inter-annual differences in the number of sub-laminae result from the presence or the absence of ; (1) distinct silt layers, (2) pelletised/diatom "hash" layers, (3) intact, un-pelletised diatom assemblages, (4) monospecific diatom blooms, and (5) exotic diatoms, such as *Thalassiothrix* mats, indicating ocean input (Kemp and Dean, 1998). SEM sediment fabric studies also identify some evidence of micro-benthic bioturbation, probably due to stronger episodes of bottom water renewal resulting from the flow of oxygenated, higher salinity, oceanic water over the sill (Kemp and Dean, 1998).

The laminated sediments are interrupted by thin (1-3 mm), light gray clay laminae and thicker massive intervals, a few cm to few tens of cm thick. The clay laminae appear separately between winter and summer layers and were deposited during abnormally high spring floods from the Cowichan River. They are more abundant in the northern part of the inlet than southern part, providing further corroboration that the major source of clastic sediments into the inlet is from north and northwest (Blais-Stevens, 1998). During the early Holocene, after initiation of diatomaceous mud deposition, there was a brief

period of rapid deposition of gray terrigenous clays with sharp lower contacts. The gray clay bed occurs as a massive layer with a sharp base and grades upward into diatomaceous mud in core 6H-5, 67-123 cm. There is palynological and silicoflagellate evidence suggesting terrestrial input of nutrients and fresh water during its deposition (written communication from Melissa McQuoid 1999). This interval is interpreted as a massive flood event at 11 k yr BP (Bornhold, 1998).

The massive units are considered to result from episodic debris flows caused by slope failure along the inlet sidewalls. There are more massive layers in the southern part of the inlet (44 at Site 1033) than northern part (22 at Site 1034), where walls are less steep (Table 2). As might be intuitively inferred, this difference in failure rate is due to the lower stability of fine grained sediments on steeper slopes (Blais-Stevens et al. 1998).

Massive layers interbedded with varved sediments record all major earthquakes in the region during the past over 7 k yr. A diatom marker horizon dated to AD 1940 provides chronological control for the youngest massive layer. Another massive layer dated at AD 1946, correlates with a large crustal earthquake on central Vancouver Island (Blais-Stevens et al. 1997). This also provides stratigraphic control near the top of the unit. There are also two other layers that are related to the AD 1700 great earthquake on Cascadia Subduction Zone (Blais-Stevens et al. 1997).

A white volcanic ash layer (1.5-2.0 cm thick) occurs at 37 mbsf in Hole 1033B, and is dated at 7,645 yr BP (Bornhold and Firth et al. 1998). This ash layer was deposited following the eruption of mount Mazama (Crater Lake, Oregon). The lowermost part of this sequence is not well laminated and contains a rich bivalve fauna

suggesting a period of 2-3 k yr of well oxygenated waters during the earliest Holocene (Blais-Stevens et al.,1998; Bornhold, 1998).

Core Description

The following description is based on Bornhold and Firth et al. (1998), but some of these data have been modified. The ^{14}C dates are calibrated. Table 1 summarizes core depth and thickness, lithology and ^{14}C dates obtained different levels.

Hole 1033B

12 cores (1H to 12H) of varying thickness (around 10 m each) were taken. Each core was partitioned into 1.5 m sections and numbered from the top. The last section is shorter and the bottom part is termed as core catcher (cc).

Core 1H (0.00-0.6 mbsf); Length cored: 0.6 m; Length recovered: 0.62 m

Age: Holocene

Description: Dark gray soupy diatomaceous mud.

Core 2H (0.6-10.1 mbsf); Length cored: 9.5 m; Length recovered: 9.88 m

Age: Holocene (2H-7, 28 cm, shell, 1,407-1,715 yr BP)

Description: Dark gray (8Y 3/1) diatomaceous mud. Mostly the core is disturbed by gas escape, making accurate assessment of the state of lamination difficult in top 6 m. Section between 6-10.1 m is less disturbed and laminae are more distinct. Laminae thickness 5-9 mm (average 6 mm) between 7.5-9.0 m and 3-4 mm between 9-9.7 m. Massive layers are at section 5, 132-150 cm; and section 6, 37-73 cm.

Core 3H (10.1-19.6 mbsf); Length cored: 9.5 m; Length recovered: 10.31 m

Age: Holocene (3H-5, 144 cm, charcoal, 2,892-3,316 yr BP)

Description: Dark gray (8Y 3/1) diatomaceous mud. Well laminated sediments with intermittent massive layers. Laminae thickness range between 3-10 mm (average 4 mm). A thin (few cm) zone of discontinuous laminae commonly occur at the base of massive layers. A lamina with abundant plant fragments occurs at section 5, 15 cm. Massive layers are at section 1, 17-22 cm; section 2, 64-100 cm, 102-109 cm, 119-136 cm; section 3, 78-83 cm, 94-111 cm; section 5, 5-20 cm, 75-126 cm; section 7, 16-20 cm, 37-86 cm.

Core 4H (19.6-29.1 mbsf); Length cored: 9.5 m; Length recovered: 10.24 m

Age: Holocene

Description: Gray to dark gray (8Y 4/1) diatomaceous mud. Well laminated sediments with intermittent massive layers. Laminae thickness range from 1 mm in section 3 to 5 mm in section 5 (average 4 mm). A thin (few cm) zone of discontinuous laminae commonly occur at the base of massive layers. Massive layers are at section 1, 0-48 cm; section 2, 5-9 cm, 22-54 cm, 99-101 cm, 126-139 cm; section 3, 72-75 cm; section 4, 59-66 cm; section 6, 92-98 cm; section 7, 73-79 cm; and CC, 11-35 cm.

Core 5H (29.1-38.6 mbsf); Length cored: 9.5 m; Length recovered: 10.11 m

Age: Holocene (5H-1, 8 cm, charcoal, 6,059-6,389 yr BP; Mazama Ash Bed, 7,645 yr BP)

Description: Gray to dark gray (8Y 4/1) diatomaceous mud. A 2 cm thick gray volcanic ash horizon (Mazama Ash Bed) occurs in section 6, 52-54 cm. The sediments is well laminated in the upper part and discontinuously laminated in the lower part. Laminae

are generally of millimeter thickness. Massive layers are at section 1, 70-85 cm; section 4, 81 to section 5, 18 cm; section 5, 64-72 cm, 113-116 cm, 133-136 cm. Intervals of discontinuous laminae occur in section 1, 78-85 cm; section 2, 69-74 cm, 137-139 cm, section 3, 6-11 cm; section 5, 54-147 cm; section 7, 0-56 cm. Traces of laminae occur in section 7, 56-89 cm.

Core 6H (38.6-48.1 mbsf); Length cored: 9.5 m; Length recovered: 10.25 m

Age: Holocene - Pleistocene (6H-2, 15 cm, shell, 8,929-9,226 yr BP; 6H-2, 60 cm, shell, 9,078-9,388 yr BP; 6H-2, 90 cm, shell, 9,246-9,474 yr BP; 6H-4, 110 cm, shell, 10,304-10,879 yr BP; 6H-5, 135, shell, 10,952-11,452 yr BP; 6H-5, 141 cm, shell, 11,003-11,643 yr BP; 6H-6, 13 cm, shell, 11,000-11,687 yr BP; 6H-6, 88 cm, shell, 11,668-12,336 yr BP).

Description: Olive gray (10Y 4/1) diatomaceous mud. It is indistinctly laminated from section 1 to section 3, 150 cm and contains traces of laminae from section 4, 0 cm to section 5, 67 cm with massive intervals at section 2, 138 cm to section 3, 17 cm, section 5, 23-31 cm. The Gray Clay Bed occurs as a massive layer with a sharp base and gradational upper contact to the diatomaceous mud in section 5, 67-123 cm.

Core 7H (48.1-57.6 mbsf)Length cored: 9.5 m; Length recovered: 9.59 m

Age: Pleistocene

Description: Gray (4GY 4/1) clay and silty clay with local faint colour banding and variable mottling throughout. Two beds of sand grading upwards to silty clay occur in section 2, 0-35 cm; and section 5, 0-54 cm.

Core 8H (57.6- 67.1 mbsf); Length cored: 9.5 m; Length recovered: 9.61 m

Age: Pleistocene

Description: Gray clay and silty clay with occasional faint colour banding and variable mottling throughout. Thin (few cm thick) beds of gray, fine to very fine sand and silt occur in section 2, 36-38 cm, 98-100 cm; section 3, 5-11 cm and 24-31 cm (bioturbated); section 4, 1-14 cm, 45-49 cm, 65-70 cm, 82-89 cm; section 5, 25-31 cm, 35-41 cm, 128-129 cm. Other minor bioturbated pockets of sand also occur at various intervals.

Core 9H (67.1-76.6 mbsf); Length cored: 9.5 m; Length recovered: 9.46 m

Age: Pleistocene

Description: Gray clay and silty clay with occasional faint colour banding and variable mottling. Thin (few cm thick) beds of gray, fine to very fine sand and silt occur in section 1, 8-10 cm, 67-71 cm; section 2, 88-96 cm, section 4, 0-36 cm, 137-142 cm; section 6, 35-46 cm, 64-67 cm, 88-90 cm. Other minor bioturbated pockets of sand or silt also occur elsewhere in the core.

Core 10H (76.6-86.1 mbsf); Length cored: 9.5 m; Length recovered: 9.44 m

Age: Pleistocene

Description: Gray clay and silty clay with occasional mottling. Thin (few cm thick) beds of gray, fine to very fine sand and silt occur in section 1, 4-9 cm; section 3, 25-31 cm, 137-142 cm; section 6, 32-38 cm, 65-70 cm, 118-129 cm.

Core 11H (86.1-95.5 mbsf); Length cored: 9.5 m; Length recovered: 8.51 m

Age: Pleistocene

Description: Gray clay and silty clay with occasional mottling. Thin (few cm thick) beds of gray, fine to very fine sand and silt occur in section 1, 122-128 cm; section 5, 35-41 cm.

Core 12H (95.5- 105.0 mbsf); Length cored: 9.5 m; Length recovered: 8.33 m

Age: Pleistocene

Description: Gray clay and silty clay with occasional mottling. Thin (few cm thick) beds of gray, fine to very fine sand and silt.

Hole 1034B

A total of 13 cores were taken (1H to 13H), sectioned and numbered like Hole 1033B.

Core 1H (0.0-4.2 mbsf); Length cored: 4.2 m; Length recovered: 4.25 m

Age: Holocene

Description: Diatomaceous mud, dark bluish gray to black in section 1, grading to dark gray. This core is disturbed by gas escape.

Core 2H (4.2-13.7 mbsf); Length cored: 9.5 m; Length recovered: 10.05 m

Age: Holocene (2H-4, 118 cm, shell, 868-1,199 yr BP)

Description: Diatomaceous mud. Sections 1 through 4 are disturbed by gas escape making assessment of the lamination difficult. Sections 5 through cc are well laminated with few massive intervals. Laminae thickness vary from 6-10 mm in sections 5 through 7. Massive layers occur in section 6, 63-82 cm, 142-144 cm.

Core 3H (13.7-23.2 mbsf); Length cored: 9.5 m; Length recovered: 10.24 m

Age: Holocene (3H-2, 113 cm, wood, 1,631-1,923 yr BP)

Description: Diatomaceous mud. The sediment is well laminated with some indistinctly laminated and massive intervals. Laminae thickness range between 5-15 mm. Indistinctly laminated intervals occur at section 2, 73-83 cm; section 7, 28-48 cm and cc. A massive layer occurs at section 5, 136-150 cm.

Core 4H (23.2-32.7 mbsf); Length cored: 9.5 m; Length recovered: 10.15 m

Age: Holocene (4H-2, 52 cm, wood, 2,781-3,156 yr BP; 4H-2, 108 cm, wood, 2,762-3,156 yr BP; 4H-4, 56 cm, wood, 4,554-4,977 yr BP)

Description: Diatomaceous mud. The sediment is well laminated with occasional massive layers at section 5, 136-150 cm. Indistinctly laminated intervals occur at section 2, 26-40 cm, 132-141 cm; section 6, 40-42 cm, 58-62 cm; section 7, 74-84 cm. Gray silty laminae are locally common (e.g. section 4, 84 cm) and a rare sand lamina occurs at section 6, 42 cm. Laminae thickness range between 6-10 mm.

Core 5H (32.7-42.2 mbsf); Length cored: 9.5 m; Length recovered: 10.15 m

Age: Holocene

Description: Diatomaceous mud. The sediment is well laminated with massive layers at section 3, 49-54 cm, 66-79 cm; section 7, 0-4 cm. Laminae thickness range between 5 mm in section 1 and 10 mm in section 2.

Core 6H (42.2-51.7 mbsf): Length cored: 9.5 m; Length recovered: 10.22 m

Age: Holocene (6H-4, 3 cm, wood, 6,303-6,632 yr BP; 6H-CC, 0 cm, shell, 7,271-7,471 yr BP)

Description: Diatomaceous mud. The sediment is well laminated with intervals of massive and indistinctly laminated layers. Massive layers occur at section 2, 89-102 cm,

141-144 cm; section 5, 66-79 cm; section 7, 3-9 cm. Indistinctly laminated intervals occur at section 2, 102-106 cm, section 5, 120-150 cm; section 6, 78-150 cm. Laminae thickness range between 5 mm in section 1 and 10 mm in section 2.

Core 7H (51.7-61.2 mbsf); Length cored: 9.5 m; Length recovered: 9.90 m

Age: Holocene-Pleistocene (Mazama Ash bed, 7,645 yr BP; 7H-4, 107 cm, shell, 8,469-8,891 yr BP; 7H-6, 129 cm, shell, 9,148-9,419 yr BP; 7H-CC, 0 cm, shell, 11,677-12,377 yr BP)

Description: Diatomaceous mud. A 2 cm thick volcanic ash (Mazama Ash Bed) occurs at section 1, 2-4 cm. The sediment is well laminated in section 1 to section 2, 66 cm. Well laminated, indistinctly laminated and massive layers occur between section 2, 66 cm through cc, 1-15 cm. Laminae thickness range between 4-8 mm.

Core 8H (61.2-70.7 mbsf); Length cored: 9.5 m; Length recovered: 9.53 m

Age: Holocene-Pleistocene (8H-2, 57 cm, shell, 9,914-10,185 yr BP; 8H-3, 53 cm, shell, 10,429-10,927 yr BP; 8H-5, 16 cm, shell, 11,098-11,944 yr BP; 8H-5, 134, shell, 10,870-11,083 yr BP; 8H-6, 66 cm, shell, 11,009-11,662 yr BP; 8H-7, 10 cm, shell, 11,702-12,361 yr BP)

Description: Olive gray diatomaceous mud. Gray silty clay (Gray Clay bed) occurs at layers in section 5. The lower of these at 92-127 cm has a sharp basal contact with underlying diatomaceous mud. The sediments are predominantly massive but contains 1-15 cm thick packets of well laminated, indistinctly laminated sediment. Shell fragments are common to abundant throughout. Laminae thickness range between 4-9 mm.

Core 9H (70.7-80.2 mbsf); Length cored: 9.5 m; Length recovered: 7.71 m

Age: Pleistocene (9H-5, 21 cm, shell, 13,557-14,067 yr BP)

Description: Olive gray to gray clayey silt. 1-20 cm thick layers of gray sand occur as interbeds.

Core 10H (80.2-89.7 mbsf); Length cored: 9.5 m; Length recovered: 9.19 m

Age: Pleistocene

Description: Gray silty clay and clayey silt. Thin beds of gray silt and sand are common in sections 1,2 and 5.

Core 11H (89.7-99.2 mbsf); Length cored: 9.5 m; Length recovered: 9.58 m

Age: Pleistocene

Description: Gray massive silty clay and clayey silt. Rare patches of sand occur in sections 1 and 5.

Core 12H (99.2-108.7 mbsf); Length cored: 9.5 m; Length recovered: 8.27 m

Age: Pleistocene

Description: Gray massive silty clay and clayey silt with thin partings of silt occur I section 1. Rare patches and disseminated grains of sand occur in sections 2,5 and 6.

Core 13H (108.7-118.2 mbsf); Length cored: 9.5 m; Length recovered: 7.98 m

Age: Pleistocene

Description: Gray massive silty clay and clayey silt. Thin laminae of sand occur in sections 1,3,4 and 5.

Material and Methods:

A total of 423 sand fraction samples, 254 from Hole 1033 B, and 169 from Hole 1034 B were studied. These samples were collected from twelve cores (1H - 12H) from

Hole 1033B, and thirteen cores (1H - 13H) from Hole 1034B. Tables 1 and 2 provide details of depth, lithology and ^{14}C dates on some of these core samples.

Each core was partitioned into 1.5 m sections and numbered from the top. The lowermost section of each core was a shorter Core Catcher (CC). Details of the standard ODP methods employed for coring and core handling are outlined in Bornhold and Firth et al. (1998) and Westbrook et al. (1994). Cores were split and analyzed for color using a Minolta spectrometer. The core was also CAT-scanned to reveal details of internal structure and composition, such as the presence of stratified and dispersed sand, ice rafted debris and subtle variations in lithology (Bornhold and Blais-Stevens, 1997).

Sub-sampling for this research was done at the Pacific Geoscience Centre (PGC), Sydney, British Columbia. The sand fraction of samples from cores was obtained by washing core sediment through a 63 μm sieve and drying at low temperature. The resultant sample residues were usually very small ranging from 0.001 g to 0.7 g out of 15 cc of core processed. A few processed samples did not have any measurable sand fraction while rare ones contained >1.0 g of sand fraction.

All foraminifera in each sample were picked and transferred to slides for subsequent identification. The number of foraminifera, total number of complete specimens, total number of broken/damaged specimens, and number of specimens of various foraminiferal species were recorded for each sample. Selected well preserved specimens were digitally photographed at the Carleton University Research Facility for Scanning Electron Microscopy (CURFEM). Identification of foraminifera was primarily

based on illustrations in the *Atlas of Common Benthic Foraminiferal Species for Quaternary Shelf Environments of Western Canada* (Patterson et al 1998).

Since a large number of samples were either barren or contained only 25-30 specimens, it was not possible to analyze them using common micropaleontological statistical techniques. Patterson and Fishbein (1989) have recommended minimum count of at least 50 specimens for indicator species having a fractional abundance of 50 % or greater. Out of 423 samples, only 58 samples fulfilled this criteria. The fractional abundance and percent error were calculated (Appendix 1) to indicate accuracy of species estimates (Patterson and Fishbein, 1989). The percent error (95 % confidence level) for each species in each sample was calculated using the standard error equation (Sxi):

$$S_{xi} = 1.96 \, [X_i \, (1 - X_i)/N]^{1/2}$$

where N is the total number of specimens in a sample, and X is the fractional abundance of a given species (Patterson and Fishbein, 1989)

Q-mode cluster analysis was carried out on 58 samples with significant populations using a technique that closely emulates results from the statistically significant "error weighted maximum likelihood" clustering method of Fishbein and Patterson (1993). This method requires that only the species present in statistically significant percent abundance of species (standard error) populations be analyzed. Although a total of 41 species of benthic foraminifera were identified, only 22 species were common enough in these 58 samples to be used for cluster analysis. Q-mode cluster

analysis was carried out on the 22 statistically significant species in these 58 samples using SPSS version 6.1 for Apple Macintosh. Euclidean distance correlation coefficients were used to measure similarity between pairs of species, and Ward's linkage method was utilized to arrange sample pairs and sample groups into a hierarchic dendrogram. This exercise produced in five subjectively determined clusters (Figure 2).

RESULTS

As only 58 of 423 samples were used in the Q-mode cluster analysis, the resultant clusters are not completely representative of the faunal distribution. Thus the biofacies description and their interpretation in terms of proxies for paleoceanographic and paleoclimatic change through the last 1.5 K yr BP in Saanich Inlet and surrounding region must be based on visual interpretation of the samples with small foraminiferal populations along with the defined clusters.

The recorded foraminiferal taxa were predominantly benthic, calcareous, shallow water forms. Planktic foraminifera were usually rare, although in a few varves and laminated samples from cores 3H-3, 4H-2, 5H-2, 5H-5 and 5H-7 in Hole 1033B they occur in significant numbers (10-50 % of the sample assemblage). Rare specimens of arcellaceans, freshwater foraminiferal analogues, were also observed, but only in the massive layers.

A large number of samples were barren (≤5 specimens), especially in the late Pleistocene section. The number of barren samples in cores 7H through 12H in Hole 1033B was 89 (Table 4), and in cores 7H through 13H in Hole 1034B was 86 (Table 5).

Biofacies Descriptions

Q-mode cluster analysis of 58 samples using 22 statistically significant species resulted in the recognition of five biofacies (Figure 2). These are defined on the basis of cluster analysis and visual examination of the data. A biofacies is defined as "part of a stratigraphic unit that is distinguished by a distinctive fossil content" (Lipps, 1993), or "a body of sediment or rock distinguished from adjacent bodies solely on the basis of fossils" (Bates and Jackson, 1984). These concepts are used in defining these biofacies. These biofacies are named after the two most abundant species in each cluster and further defined on the basis of additional species present. The more abundant species usually occur in all samples comprising a cluster, although there are some exceptions. These biofacies correspond to distinct stratigraphic intervals

1. ***Stainforthia feylingi - Buccella frigida*** **biofacies** : This biofacies (18 samples) is dominated by *Stainforthia feylingi* which accounts for 26 to 97 % of the assemblage. The other significant species is *Buccella frigida* which accounts for 7 to 71 % of the population. Other common species are *Lobatula fletcheri, Nonionella stella, Bolivinellina pacifica, Fissurina* spp, *Trochammina* spp. and *Cribroelphidium* spp. are less common.

2. ***Buccella frigida - Lobatula fletcheri*** **biofacies** : This biofacies (16 samples) is dominated by *Buccella frigida* (18 - 52% of the assemblage) and *Lobatula fletcheri* (6 - 38% of the assemblage). Other species occurring in this biofacies are *Buliminella eligantissima , Nonionella stella, Stainforthia feylingi, Cribroelphidium halladense, Cribroelphidium foraminosum* and *Fissurina* spp. This biofacies is also characterized by

the common occurrence of planktic foraminifera (up to 34 % of the assemblage). Only a few samples have significantly large number of foraminiferal specimens (up to 1,000).

3. *Nonionella stella - Stainforthia feylingi* biofacies : This biofacies (4 samples) is dominated by *Nonionella stella* (45 - 81 % of the assemblage) and *Stainforthia feylingi* (0 - 43 % of the assemblage). *Cribroelphidium excavatum, Cribroelphidium halladense* and *Buccella frigida* occur commonly while *Bolivinellina pacifica, Nonionella digitata, Fissurina* spp., *Trochammina* spp. and *Buliminella eligantissima* are rare. There are five samples in the bottom 59 cm (70-129 cm) of core 6H-5 in Hole 1033B (see Table 4) which represent the Younger Dryas event (sample sheet provided by Kim Conway), of which three samples are barren. The top sample (70-73 cm) and the bottom sample (126-129 cm) contain fauna of the *Nonionella stella - Stainforthia feylingi* biofacies.

4. *Islandiella helenae - Spirosigmoilina tenuis* biofacies : This biofacies (12 samples) is dominated by *Islandiella helenae* (21 - 42 % of the assemblage), *Islandiella norcrossi* (6 - 46 % of the assemblage) and *Spirosigmoilina tenuis* (8 - 43 % of the assemblage). Other common species include *Cribroelphidium excavatum, Cribroelphidium foraminosum, Buccella frigida, Lobatula fletcheri,* and *Nonionella labradorica, Nonionella stella* are infrequent. The richest sample, 7H-1/29-32 cm in Hole 1033B (1760 specimens) belongs to this biofacies.

5. *Siphonaperta stalkeri - Cribroelphidium excavatum* biofacies : This biofacies (8 samples) is dominated by *Siphonaperta stalkeri* (0 - 68 % of the assemblage) and *Cribroelphidium excavatum* (7 - 66 % of the assemblage). Other common species are *Nonionella digitata, Islandiella helenae, Islandiella norcrossi* and *Rosalina* spp. Other

rare species include *Cribroelphidium halladense, Cribroelphidium foraminosum, Cribroelphidium microgranulosum, Cassidulina reniforme* and *Nonionella stella.*

Age:

Twelve ^{14}C dates were obtained from Hole 1033B (Table 1) and 17 ^{14}C dates were obtained from Hole 1034B (Table 2). Most of the dates are from the Holocene with a few from late Pleistocene. The youngest date available from Hole 1033B was 1,407-1,715 yr BP for sample 2H-7, 28 cm, and the oldest date obtained from this core was 11,668-12,336 yr BP for the sample 6H-6, 88 cm. The youngest date available from Hole 1034B was 868-1,199 yr BP for the sample 2H-4,118 cm, and the oldest date in this core was 13,557-14,067 yr BP for sample 9H-5, 21 cm. The Mazama Ash Bed was identified at 37 mbsf at Site 1033 and 51 mbsf at Site 1034 and was dated at 7,645 yr BP.

DISCUSSION

The *Siphonaperta stalkeri - Cribroelphidium excavatum* biofacies (Figure 2) occurs in cores 7H, 8H and 12H in Hole 1033B and in one sample of core 9H in Hole 1034B. These samples are mainly gray clay, silty clay with beds of fine sand. No ^{14}C dates are available for any core sample over this interval, but based on the stratigraphic position of the core samples and oldest available ^{14}C dates (13,557-14,067 yr BP for sample 8H-7, 10 cm in Hole 1034B and 11,668-12,336 yr BP for sample 6H-13 in Hole 1033B) an age, >13,500 yr BP can assigned. These sediments are oldest cored in the Saanich Inlet. A total of 104 samples from cores 7H through 12H in Hole 1033B, and 82

samples from cores 9H through 13H in Hole 1034B were studied, of which only 10 and 11 samples respectively yielded workable foraminiferal populations having ≥ 50 specimens. Most of these samples were absolutely barren and only 10 samples in Hole 1033B and 7 samples in Hole 1034B contained few (< 25) specimens of benthic foraminifera.

Prior to 13,500 yr BP, the Saanich Inlet region was covered with ice and deglaciation had just begun. Huntley et al. (ms) define this time as early to middle deglacial phase (15,000 to 13,000 yr BP). During this time deglaciation began first at peaks and high ridges on Vancouver Island. As a result ice was increasingly confined to valleys and coastal lowlands. Meltwater and sediment were filling Saanich Inlet. Isostatically depressed lowland areas were inundated by the sea, and sea level in the region was higher relative to land than it is today. The late glacial marine limit is about 90 m asl in the Saanich Inlet area (Huntley et al. 1998). The large number of barren samples in this section are related to low very salinity levels due to the massive influx of freshwater.

Although *Siphonaperta stalkeri* and *Cribroelphidium excavatum* are dominant species in this biofacies, the most significant species of this biofacies are *Cassidulina reniforme, Islandiella helenae, Islandiella norcrossi, Cribroelphidium microgranulosum* and *Nonionella stella*. Both *Cassidulina reniforme* and *Islandiella helenae* are arctic species (Guilbault et al. 1997 and Patterson et al. 1995) and *Islandiella norcrossi, Cribroelphidium microgranulosum* and *Nonionella stella* are temperate species (Guilbault et al. 1997 and Patterson et al. 1995). The lower abundance of *Cassidulina reniforme* in

this biofacies is due to its susceptibility to dissolution (Patterson et al. 1995). This fauna is typical of low salinity glacial marine conditions in Saanich Inlet.

The *Islandiella helenae - Spirosigmoilina tenuis* biofacies (Figure 2) occurs in cores 7H-2 and 7H-5 in Hole 1033B and in cores 9H-1, 9H-2, 9H-3 and 9H-4 in Hole 1034B. These samples are mainly gray clay, silty clay with beds of fine sand. There are no ^{14}C dates for core 7H in Hole 1033B, but it was deposited during the late Pleistocene, as it is stratigraphically below the available ^{14}C date of 11,668-12,336 yr BP in core 6H-6. Since sample 9H-5 in Hole 1034B is dated as 13,557-14,067 yr BP, an age of ~12,500 - ~13,500 yr BP can be assigned to all these samples.

The time represented by *I. Helenae - S. tenuis* biofacies corresponds with the middle to late deglaciation phase (14,000 to12,000 yr BP) of Huntley et al. (ms). As the process of deglaciation continued, the central Strait of Georgia had become deglaciated and ice in Saanich Inlet retreated to valley outlets, coastal narrows and bedrock sill at the edge of Satellite Channel. The flux of melt water and sediment into Saanich Inlet was maximal between 13,500 and 12,500 yr BP (Huntley et al. 1998). Late deglacial deltaic deposits and wave cut terraces at an elevation of 40 m asl on Saanich Peninsula indicate that sea-level fell relative to land as deglaciation progressed. This was because glacio-isostatic rebound was more pronounced than eustatic sea-level rise in this region (Huntley et al. ms).

I. Helenae - S. tenuis biofacies is dominated by characteristic temperate and arctic foraminiferal species (Guilbault et al. 1997), such as *Spirosigmoilina tenuis, Islandiella helenae* and *Islandiella norcrossi* (Patterson et al. 1995). Other minor components of this

biofacies, like *Nonionella labradorica* and *Nonionella stella* also occur in icy cold temperate waters and glacial marine sediments (Vilks, 1980; Guilbault et al. 1997). In Saanich Inlet this biofacies indicates a low salinity subglacial environment.

The *Nonionella stella - Stainforthia feylingi* biofacies (Figure 2) occurs in only four samples of core 6H-5 in Hole 1033B in indistinctly laminated diatomaceous muds with massive intervals. Two ^{14}C dates are available from this core, indicating a late Pleistocene deposition (10,952-11,452 yr BP and 11,003-11,643 yr BP). This time coincides with the Late Pleistocene - early post-glacial phase (12,000 to 10,000 yr BP) of Huntley et al. (ms). During this time Cowichan Valley and adjacent parts of southeastern Vancouver Island were free of ice (Alley and Chatwin, 1979; Huntley et al. ms.). The flux of meltwater and sediment decreased markedly as ice disappeared. Relict wave-cut platforms and raised beaches, ranging in elevation from 5 to 20 m asl, indicate that glacio-isostatic rebound continued after deglaciation (Huntley et al. ms) and by 11,000-10,000 yr BP sea-level further fell relative to land by several tens of meters lower than today. Water level over the sill at north end of the Saanich Inlet was less, consequently circulation was different than now (Huntley et al. 1998).

Evidence for the Younger Dryas (YD) sudden cooling event has been detected on the British Columbia coast during this time period (11,000 - 10,000 yr BP) (Mathewes et al. 1993; Patterson et al. 1995). Key indicator species such as *Cassidulina reniforme, Islandiella helenae* and *Islandiella norcrossi* which are useful YD event indicators elsewhere on the British Columbia shelf do not occur in *N. stella - S. feylingi* biofacies. Thus it is difficult to recognize the YD event in the Saanich Inlet cores.

Nonionella stella, Cribroelphidium excavatum and *Cribroelphidium halladense* are known temperate species (Patterson et al. 1995; Guilbault et al. 1997). *Stainforthia feylingi* also commonly occurs in arctic to cold boreal environments (Knudsen and Seidenkrantz, 1994) and is a very common species in "glacial marine " biofacies from Dixon Entrance, northwest British Columbia (Guilbault et al. 1997). This biofacies is indicative of a transition phase from glacial to temperate climate. The salinity in Saanich Inlet was still low because of continued influx of melt water and periodic massive flooding due to breakage of the ice dams which dammed lakes of melted water. For example, the deposition of grey clay bed in the core 6H-5, 67-123 cm in Hole 1033 is interpreted as a massive flood event at 11,000 yr BP (Bornhold, 1998).

The *Stainforthia feylingi - Buccella frigida* biofacies (Figure 2) is found mainly in cores 5H, and 6H in Hole 1033B (29- 48 mbsf) and in a few samples from core 2H-5 and 7H-5, and one sample 8H-1/140-143 cm (51-63 mbsf) from Hole 1034B. The sediment type typically holding this biofacies is primarily massive mud layers formed by subaqueous sediment flows. In Hole 1033B this fauna is most common in the early to mid Holocene, between 10,000- 6,000 yr BP. This time partly corresponds with the Early (10,000-8,000 yr BP) and Middle (8,000- 4,000 yr BP) Holocene - post-glacial phase of Huntley et al. (ms). Relative sea-level continued to fall during the early Holocene in response to glacio-isostatic rebound (Mathewes et al. 1970; Clague et al. 1982; Huntley at al. ms.). By the mid Holocene eustatic rise in sea-level began in response to the middle-late Holocene marine transgression. By about 4,000 yr BP, sea-level had risen to near its present position (Mathewes et al. 1970; Clague et al. 1982; Huntley at al. ms.) and

present day oceanographic conditions were established in Saanich Inlet (Huntley et al. 1998).

The *Stainforthia feylingi - Buccella frigida* biofacies compares very well with the *Lobatula fletcheri* biofacies of Blais-Stevens and Patterson (1998), because of the common occurrence of *Lobatula fletcheri* in all samples and overall similarity in faunal composition. Blais-Stevens and Patterson (1998) subdivided this biofacies into the *Stainforthia feylingi* sub-biofacies and *Buccella frigida* sub-biofacies. They reported that *Stainforthia feylingi* inhabits muddy basin trough (88-90 m deep) and also low oxygen shallower sandy substrates, and Buccella frigida and associated species inhabit coarse sandy bottom environments in the bay (10-31 m deep).

The mixing of *Stainforthia feylingi* and *Buccella frigida* observed in the *Stainforthia feylingi - Buccella frigida* biofacies is probably due to faunal mixing, as the massive layers where these forms are typically found in Hole 1033B were deposited by subaqueous sediment flows from shallower depths of the inlet to the bottom of the trough. In most cases *Stainforthia feylingi* is autochthonous while species such as *Buccella frigida* are allochthonous.

Stainforthia feylingi. Nonionella stella and *Bolivinellina pacifica* were able to withstand the dysoxic/anoxic environmental conditions which had developed in the deeper (>90 m) parts of the Saanich Inlet by the mid Holocene. *Stainforthia feylingi* is widely known to occur in dysoxic/anoxic environments, e.g. polluted fjörds of southeastern Norway (Alve, 1990), deep estuarine environments in eastern Canada (Miller et al. 1982), coastal fjörds in northern Europe (Murray, 1985) and Effingham Inlet, Vancouver Island

(Patterson et al. In press). *Nonionella stella* and *Bolivinellina pacifica* characterize similar environments in the Santa Barbara Basin of the California Borderland (Douglas, 1981; Douglas and Heitman, 1979; Bernhardt et al. 1997). The consistent occurrence of stained *Stainforthia feylingi* and *Bolivinellina pacifica* in the deepest parts of the Effingham Inlet on Vancouver Island suggests that these taxa normally live in dysoxic waters (Patterson et al. in press). Although *Nonionella stella* prefers to live under dysoxic/anoxic conditions (Bernhardt et al. 1997), this species was reported living infaunally (within an anoxic sediment layer) in an oxygenated environment of Effingham Inlet (Patterson et al. In press). The presence of *Trochammina* spp. in the *Stainforthia feylingi - Buccella frigida* biofacies is also significant and supports dysoxic/anoxic origin of this biofacies, as these forms were also reported from deep (115-209 m) dysoxic/anoxic environments of the Effingham Inlet (Patterson et al., 1998). This biofacies records the establishment of modern anoxic conditions at the bottom the inlet and development of normal marine conditions in the shallower oxic regions.

The *Buccella frigida - Lobatula fletcheri* biofacies (Figure 2) occurs mainly in the cores 2H through 5H (0.6-29 mbsf) and in one sample in core 6H in Hole 1033B. This biofacies was found mainly in massive and breccia layers, and only two samples 3H-3, 67-70 cm and 5H-1, 60-63 cm hosting this biofacies are varves. The time represented by cores 5H through 2H is between 6,000 - <1,000 yr BP. Present day oceanographic conditions were established in Saanich Inlet by 4,000 yr BP (Huntley et al. ms.).

The presence of *Cribroelphidium* spp. and *Buliminella eligantissima* also indicate shallow marine well oxygenated environments (Snyder, 1989; Patterson, 1993; Patterson

et al. 1995). This biofacies is indicative of shallow marine, temperate environments, since these two dominant species have similar habits and are known to inhabit shallow marine waters on the British Columbia coast (Patterson, 1993, Patterson et al. 1995, Guilbault et al. 1997, Patterson et al. In press). This biofacies closely compares with sub-biofacies *Buccella frigida* from the bays of Saanich Inlet described by Blais-Stevens and Patterson, 1998).

The occurrence of such a microfaunal assemblage in the cores of Saanich Inlet represents transporting and reworking of the fauna from shallow marine, well oxygenated environments.

It is clear from the above discussion that the distribution of benthic foraminiferal biofacies in Saanich Inlet has been mainly controlled by deglaciation processes and associated relative sea-level changes, especially during late Pleistocene and Early Holocene. Once modern oceanographic conditions developed during mid Holocene, changes in climate and in oxygen content of bottom waters played major role in the distribution of benthic foraminiferal biofacies.

FAUNAL REFERENCE LIST

ORDER FORAMINIFERIDA Eichwald, 1830

Following is the list of foraminiferal species observed in this study. Identification and naming of the taxa are based on Patterson et al. 1998. Italicized names enclosed with in brackets indicate the original generic designations. Plate and figure numbers refer to taxa illustrated here.

Angulogerina angulosa (Williamson), 1858, (*Uvigerina*), (Pl. 2, Fig. 2)

Angulogerina fluens Todd, 1948

Astrononion gallowayi Loeblich and Tappan, 1953

Bolivinellina pacifica (Cushman and McCulloch), 1942, (*Bolivina acerosa* Cushman var.) (Pl. 1, Fig. 16, 20)

Buccella depressa (Anderson), 1952, (Pl. 1, Fig. 10)

Buccella frigida (Cushman), 1922, (*Pulvinulina*), (Pl. 1, Fig. 3 and Pl. 2, Fig. 13)

Buliminella eligantissima (d'Orbigny), 1839, (*Bulimina*), (Pl. 2, Fig. 14, 15)

Buliminella sp.

Cassidulina reniforme (Norvang), 1945, (*Cassidulina crassa* d'Orbigny var.), (Pl. 2, Fig. 12, 18)

Cribroelphidium excavatum (Terquem), 1876, (*Polystomella*), (Pl. 1, Fig. 1, 7)

Cribroelphidium foraminosum (Cushman), 1939, (*Elphidium hughesi* Cushman and Grant var.), (Pl. 1, Fig. 12, 14)

Cribroelphidium halladense (Brotzen), 1943, (*Elphidium*), (Pl. 1, Fig. 13)

Cribroelphidium microgranulosum (Galloway and Wissler in Thalmann), 1951 (*Elphidium*) (Pl. 2, Fig. 7, 8)

Chilostomella oolina Schwager, 1878

Euuvigerina juncea (Cushman and Todd), 1941, (*Uvigerina*), (Pl. 2, Fig. 16)

Euuvigerina sp.

Favulina melo (d'Orbigny), 1839, (*Oolina*), (Pl. 2, Fig. 3)

Fissurina eburnea (Buchner), 1940, (*Lagena*), (Pl. 2, Fig. 5)

Fissurina sp.

Homalohedra borealis (Buchner), 1954, (*Oolina*), (Pl. 2, Fig. 9)

Homalohedra guntheri (Earland), 1934, (*Lagena*), (Pl. 1, Fig. 2)

Homalohedra sp.

Hyalinonetrion clavatum (d'Orbigny), 1846, (*Oolina*), (Pl. 2, Fig. 10)

Islandiella helenae (Feyling-Hansen and Buzas), 1976 (Pl. 1, Fig. 8)

Islandiella norcrossi (Cushman), 1933, (*Cassidulina*), (Pl. 2, Fig. 6)

Lagena striatocollis (d'Orbigny), 1839, (*Oolina*), (Pl. 1, Fig. 18)

Lobatula fletcheri (Galloway and Wissier), 1927, (*Cibicides*), (Pl. 1, Fig. 4, 5)

Miliammina fusca (Brady), 1870, (*Quinqueloculina fusca*)

Nonionella digitata (Norvang), 1945, (*Nonionella turgida* (Williamson) var.), (Pl. 2, Fig. 11)

Nonionella labradorica (Dawson), 1860, (*Nonionina scapha* var. *labradorica*), (Pl. 2, Fig. 20)

Nonionella stella (Cushman and Moyer), 1930, (*Nonionella miocenica* Cushman var.), (Pl. 1, Fig. 15)

Palliolatella frangens (Buchner), 1940 (*Lagena*), (Pl. 2, Fig. 19)

Protoglobobulimina elongata (d'Orbigny), 1826, (*Bulimina*), (Pl. 1, Fig. 11)

Quinqueloculina sp.

Rosalina columbiensis (Cushman), 1925, (*Discorbis*)

Rosalina sp.

Stainforthia feylingi (Knudsen and Seidenkrantz), 1993, (Pl. 1, Fig. 19)

Siphonaperta stalkeri (Loeblich and Tappan), 1953, (*Quinqueloculina*), (Pl. 1, Fig. 9 and Pl. 2, Fig. 4, 17)

Spirosigmoilina tenuis (Czjzek), 1848, (*Quinqueloculina*), (Pl. 1, Fig. 17 and Pl. 2, Fig. 1)

Trochammina charlottensis Cushman, 1925

Trochammina nana (Brady), 1881, (*Haplophragmium*)

ACKNOWLEDGMENTS

This research was supported by a NSERC research grant and NSERC collaborative special grant to RTP.

REFERENCES

Alley, N. F. and Chatwin, S. C., 1979. Late Pleistocene history and geomorphology, southwestern Vancouver Island, British Columbia. Canadian Journal of Earth Sciences, v. 16, p. 1645-1657.

Alve, E. 1990., Variations in estuarine foraminiferal assemblages with diminishing oxygen conditions in Drammensfjord, SE Norway: Paleoecology, Biostratigraphy, Paleoceanography and Taxonomy of Agglutinated Foraminifera, NATO Series, C, Mathematical and Physical Sciences, v. 327, p. 661-694.

Bates, R. L. and Jackson, J. A. 1984. Dictionary of Geological terms. American Geological Institute. 571 P.

Bernhard, J. M., Sen Gupta, B. K., & Borne, P. F., 1997. Benthic foraminiferal proxy to estimate dysoxic bottom-water oxygen concentrations: Santa Barbara Basin, U.S. Pacific continental margin. Journal of Foraminiferal Research, v. 27, p. 301-310.

Blais, A., 1995. Foraminiferal biofacies and Holocene sediments from Saanich Inlet, British Columbia: Implications for environmental and neotectonic research, unpublished Ph.D. dissertation, Carleton University, Ottawa, Ontario, Canada, 280 p.

Blais-Stevens, A. 1998. Holocene spring flood deposits in Saanich Inlet, BC: a paleoclimatic record ?. Geological Association of Canada/Mineralogical Association of Canada, 1998 Meeting, Quebec City. Abstract with Programme, p. A-19.

Blais-Stevens, A., Clague, J. J., Bobrowsky, P. T.,& Patterson, R. T. 1997. Late Holocene sedimentation in Saanich Inlet, British Columbia, and its paleoseismic implications. Canadian Journal of Earth Sciences, v. 34, p.1345-1357.

Blais-Stevens, A. & Patterson, R. T., 1998. Environmental indicator potential of foraminifera from Saanich Inlet, Vancouver Island, British Columbia, Canada. Journal of Foraminiferal Research, v. 28, p. 201-219.

Blais-Stevens, A., Clague, J. J. & Bobrowsky, P. T. 1998. Holocene sedimentation in Saanich Inlet, B. C.: Implications for prehistoric earthquake history. Geological Association of Canada/Mineralogical Association of Canada, 1998 Meeting, Quebec City. Abstract with Programme.

Blaise, B., Clague, J. J., and Mathewes, R. W. 1990. Time of maximum Late Wisconsin glaciation, west coast of Canada. Quaternary Research, v. 34: 282-295.

Blyth, H. E. & Rutter, N. W., 1993. Surficial geology of the Sydney area. Ministry of Energy, Mines and Petroleum Resources, BC., Open file map 1993-24, NTS 92B/11.

Blyth, H. E., Rutter, N. W., & Sankeralli, L. M., 1993. Surficial geology of the Shawnigan Lake area. Ministry of Energy, Mines and Petroleum Resources, BC. Open file map 1993-26, NTS 92B/12.

Bobrowsky, P. T. & Clague, J. J., 1990. Holocene sediments from Saanich Inlet, British Columbia, and their neotectonic implications. In Current Research, part E. Geological Survey of Canada Paper 90-1E, p. 251-256.

Bornhold, B. D. 1998. The Ocean Drilling Program Leg 169 S in Saanich Inlet, British Columbia- Overview. Geological Association of Canada/ Mineralogical Association of Canada Annual Meeting, Quebec City. Abstract with Programme, p. .

Bornhold, B. D. & Blais-Stevens, A. 1997. Core Baselines. In, Ultra-high resolution climatic, oceanographic, biological and geochemical records in Saanich Inlet, British Columbia, ODP Leg 169 S. 1st Annual report (M. J. Whiticar), Centre for Earth & Ocean Research, University of Victoria, p. 6-9.

Bornhold, B., Firth, J. V. et al. 1998. Proc. ODP. Init. Repts., 169S: College Station, Texas (Ocean Drilling Program), 138 p.

Clague, J. J., 1994. Quaternary stratigraphy and history of south-coastal British Columbia. In Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, (ed.) J. W. H. Monger, Geological Survey of Canada, Bulletin 481, p.181-192.

Clague, J. J. and Mathewes, R. W. 1989. Early Holocene thermal maximum in western North America: New evidence from Castle Peak, British Columbia. Geology, v. 17: p. 277-280.

Clague, J. J. and Mathewes, R. W. 1996. Neoglaciation, Glacier-dammed lakes, and Vegetation change in Northwestern British Columbia, Canada. Arctic and Alpine Research, v. 28, p.10-24.

Clague, J. J., Harper, J. R., Hebda, R. J., and Howes, D. E. 1982. Late Quaternary sea-level and crustal movements, coastal British Columbia. Canadian Journal of Earth Sciences, v. 19, p. 597-618.

Cowan, E. A., Carlson, P. R. and Powell, R. D. 1996. The marine record of the Russel Fiord outburst flood, Alaska, U.S.A. Annals of Glaciology, v. 22, p.194-199.

Culver, S. J. and Buzas, M. A. 1985. Distribution of Recent benthic foraminifera off the North American Pacific Coast from Oregon to Alaska. Smithsonian Contribution to Marine Sciences, no. 26, 234 P.

Douglas, R. G., 1981. Paleoecology of continental margin basins: A modern case history from the borderland of Southern California, in Douglas, R. G., Colburn, I. P. & Grosline, D. S. (eds.), Depositional System of Active Continental Margin Basins: Short Course Notes: SEPM Pacific Section, San Francisco, p. 121-156.

Douglas, R. G. & Heitman, H. L., 1979. Slope and basin benthic foraminifera of the California borderland: SEPM Special Publication, v. 27, p. 231-246.

Fishbein, E. and Patterson, R. T. 1993. Error-weighted maximum likelihood (EWML): a new statistically based method to cluster quantitative micropaleontological data. Journal of Paleontology, 67, p. 475-486.

Friele, P.A. and Hutchinson, I. 1993. Holocene sea-level change on the central-west coast of Vancouver Island, British Columbia. Canadian Journal of Earth Sciences, v. 30, p. 832-840.

Gross, M. G., Gucluer, S. M., Creager, J. S. and Dawson, W. A., 1963. Varved marine sediments in a stagnant fjord. Science, v. 141, p. 918-919.

Gucluer, S. M. & Gross, M. G. 1963. Recent marine sediments in Saanich Inlet, a stagnant marine basin. Limnology and Oceanography, v. 9, p. 359-376.

Guilbault, J-P., Patterson, R. T., Thomson, R. E., Barrie, J. V. and Conway, K. W. 1997. Late Quaternary paleoceanographic changes in Dixon Entrance, Northwest British Columbia, Canada: Evidence from the foraminiferal faunal succession. Journal of Foraminiferal Research, v. 27, p. 151-174.

Holland, S. S. 1980. Landforms of British Columbia, a physiographic outline. British Columbia Ministry of Energy, Mines and Petroleum Resources, Bulletin, v.48, 138 p.

Huntley, D. H. 1999. Surficial geology and geomorphology of the Saanich Inlet area, southeastern Vancouver Island, British Columbia. Final report (ODP leg 169 S).

Huntley, D. H., Bobrowsky, P. T. and Clague, J. J. 1998. Late Wisconsinan deglaciation of Saanich Inlet, southeastern Vancouver Island, British Columbia. Geological association of Canada/Mineralogical Association of Canada, Abstract Volume, A-82, Quebec City.

Huntley, D. H., Bobrowsky, P. T. and Clague, J. J. (ms). Ocean Drilling program Leg 169S: Surficial Geology, Stratigraphy and geomorphology of the Saanich Inlet area, southeastern Vancouver Island, British Columbia. Marine Geology (submitted).

Hutchinson, I., Clague, J. J. & Mathews, R. W. 1997. Reconstructing the tsunami record on an emerging coast: a case study of Kanim Lake, Vancouver Island, British Columbia, Canada. Journal of Coastal Research, v. 13, p. 545-553.

Kemp, A. E. S., 1996. Palaeoclimatology and palaeoceanography from laminated sediments. Geol. Soc. Spe. Publ. No. 116. The Geological Society, London., 258 p.

Kemp, A. E. S. & Dean, 1998. Ultra-high resolution paleoclimatology and paleoceanography from Holocene laminated sediments: preliminary results from Saanich Inlet, ODP, Leg 169 S. Geological Association of Canada/ Mineralogical Association of Canada, Annual Meeting, Quebec City. (Abstract).

Knudsen, K. L. & Seidenkrantz, M. S., 1994. Stainforthia feylingi: New species from Arctic to Sub-arctic environments, previously recorded as Fursenkoina schreibersiana (Czjzek): Contributions from the Cushman Foundation of Foraminiferal Research, Spe. Publ. No. 32, p. 5-13.

Lipps, J. H. 1993. Fossil Prokaryotes and Protists. Blackwell Scientific Publ. 342 P.

Luternauer, J. L., Clague, J. J., Conway, K. W., Barrie, J. V., Blaise, B., and Mathewes, R. W. 1989. Late Pleistocene terrestrial deposits on the continental shelf of western Canada: Evidence for rapid sea-level change at the end of the last glaciation. Geology, v. 17, p. 357-360.

Mathewes, R. W., Fyles, J. G. and Nasmith, H. W. 1970. Post-glacial crustal movements in southwestern British Columbia and adjacent Washington State. Canadian Journal of Earth Sciences, v. 7, p. 690-702.

Mathewes, R. W., Heusser, L. E. and Patterson, R. T. 1993. Evidence for a Younger Dryas-like cooling event on the British Columbia coast. Geology, v. 21, p. 101-104.

Miller, A. A., Mudie, P. J. and Scott, D. B. 1982. Holocene history of Bedford Basin, Nova Scotia: foraminifera, dinoflagellate and pollen records. Canadian Journal of Earth Sciences, v.19, p. 2342-2367.

Murray, J. W. 1985. Recent foraminifera from the North Sea (Forties and Ekofisk areas) and the continental shelf of west of Scotland. Journal of Micropalaeontology, v. 4, p. 117-125.

Patterson, R. T. 1993. Late Quaternary benthic foraminiferal assemblages and paleoceanography of Queen Charlotte Sound and southern Hecate Strait, British Columbia. Journal of Foraminiferal Research, v. 23, p. 1-18,

Patterson, R. T. and Cameron, B. E. B. 1991. Foraminiferal biofacies succession in the late Quaternary Fraser River Delta, British Columbia. Journal of Foraminiferal Research, v. 21, p. 228-243.

Patterson, R. T., Guilbault, J.-P., Thomson, R. E., and Luternauer, J. L. 1995. Foraminiferal evidence of Younger Dryas isochronous cooling on the British Columbia Shelf, west coast of Canada. Geographie Physique et Quaternaire, v. 49, p. 409-428.

Patterson, R.T., Burbridge, S. M. and Luternauer, J. L., 1998. Atlas of common benthic foraminiferal species for Quaternary shelf environments of western Canada. Geological Survey of Canada Bulletin 503, 91 p.

Patterson, R. T. & Fishbein, E., 1989. Re-examination of the statistical methods used to determine number of point counts needed for micropaleontological quantitative research. Journal of Paleontology, v. 63, p. 245-248.

Patterson, R. T., Guilbault, J. P. & Thomson, R. E., In Press. Oxygen level control on foraminiferal assemblage distribution in Effingham Inlet, Vancouver Island, British Columbia. Journal of Foraminiferal Research.

Reinhardt, E. G., Easton, N. A., and Patterson, R. T. 1996. Foraminiferal evidence of Late Holocene sea-level change and Amerindian site distribution at Montague Harbour, British Columbia. Geographie Physique et Quaternaire, v. 50, p. 35-46.

Sancetta, C. & Calvert, S. E. 1988. The annual cycle of sedimentation in Saanich Inlet, British Columbia: implications for the interpretation of diatom fossil assemblages. Deep-Sea Research, v. 35, p. 71-90.

Snyder, S. W., Hale, W. R. and Kontrovitz, M. 1990. Distributional patterns of modern benthic foraminifera of the Washington Shelf. Micropaleontology, v. 36, p. 245-258.

Thomson, R. E. 1981. Oceanography of the British Columbia coast. Canadian Special Publication of Fisheries and Aquatic Sciences, no. 56, 291 p.

Vilks, G. 1980. Postglacial basin sedimentation on Labrador Shelf. Geological Survey of Canada, Paper 78-28, 28 p.

Westbrook, G. K., Carson, B., Musgrave, R. J. et al. 1994. Proc. ODP, Init. Repts., 146 (Pt. 1): College Station, TX (Ocean Drilling Program).

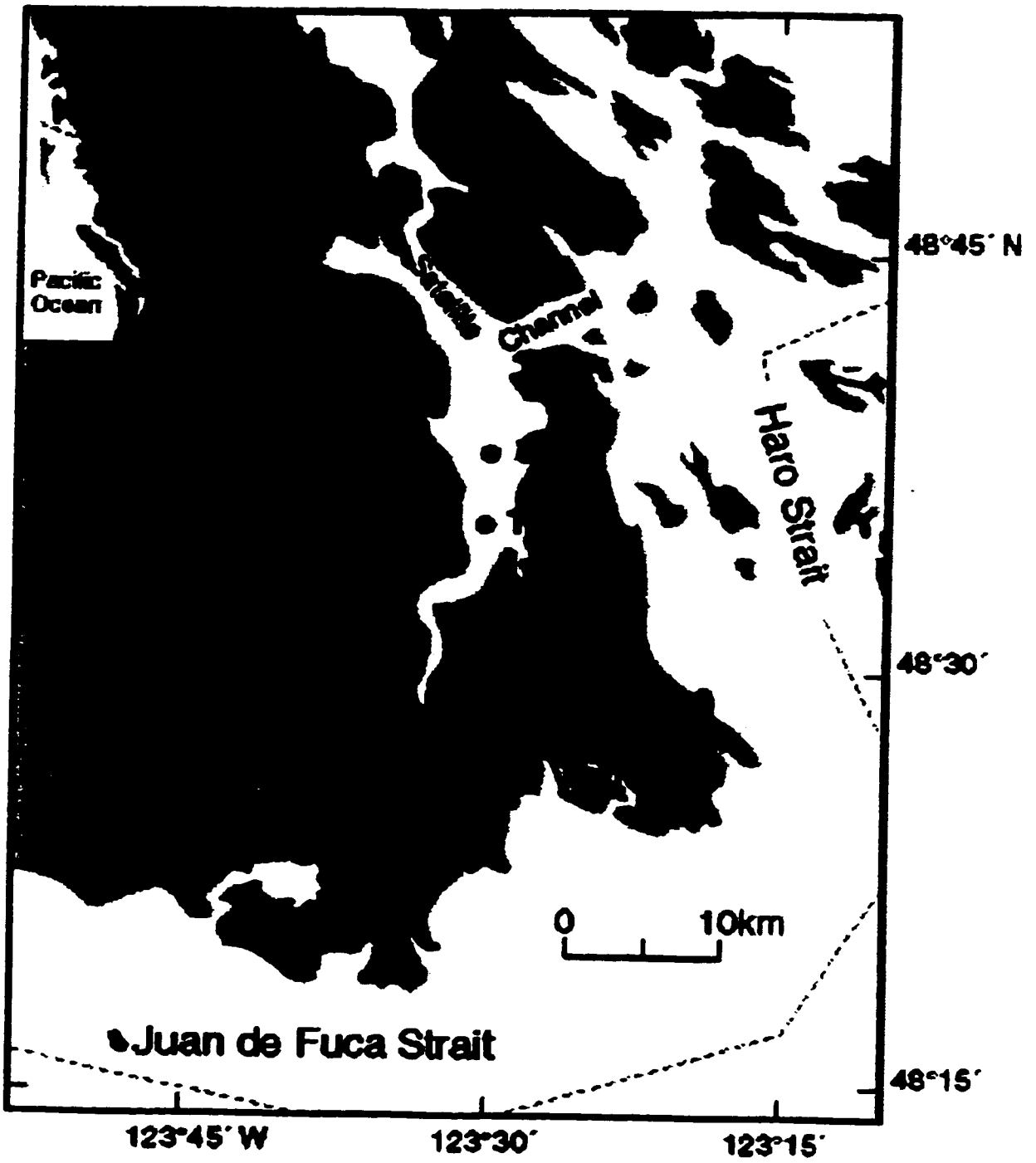
Whiticar, M. J. et al. 1997. Ultra-high resolution climatic, oceanographic, biological and geochemical records in Saanich Inlet, British Columbia. Ocean drilling program Leg 169 S. First Year annual report. Centre for Earth and Ocean Research, University of Victoria.

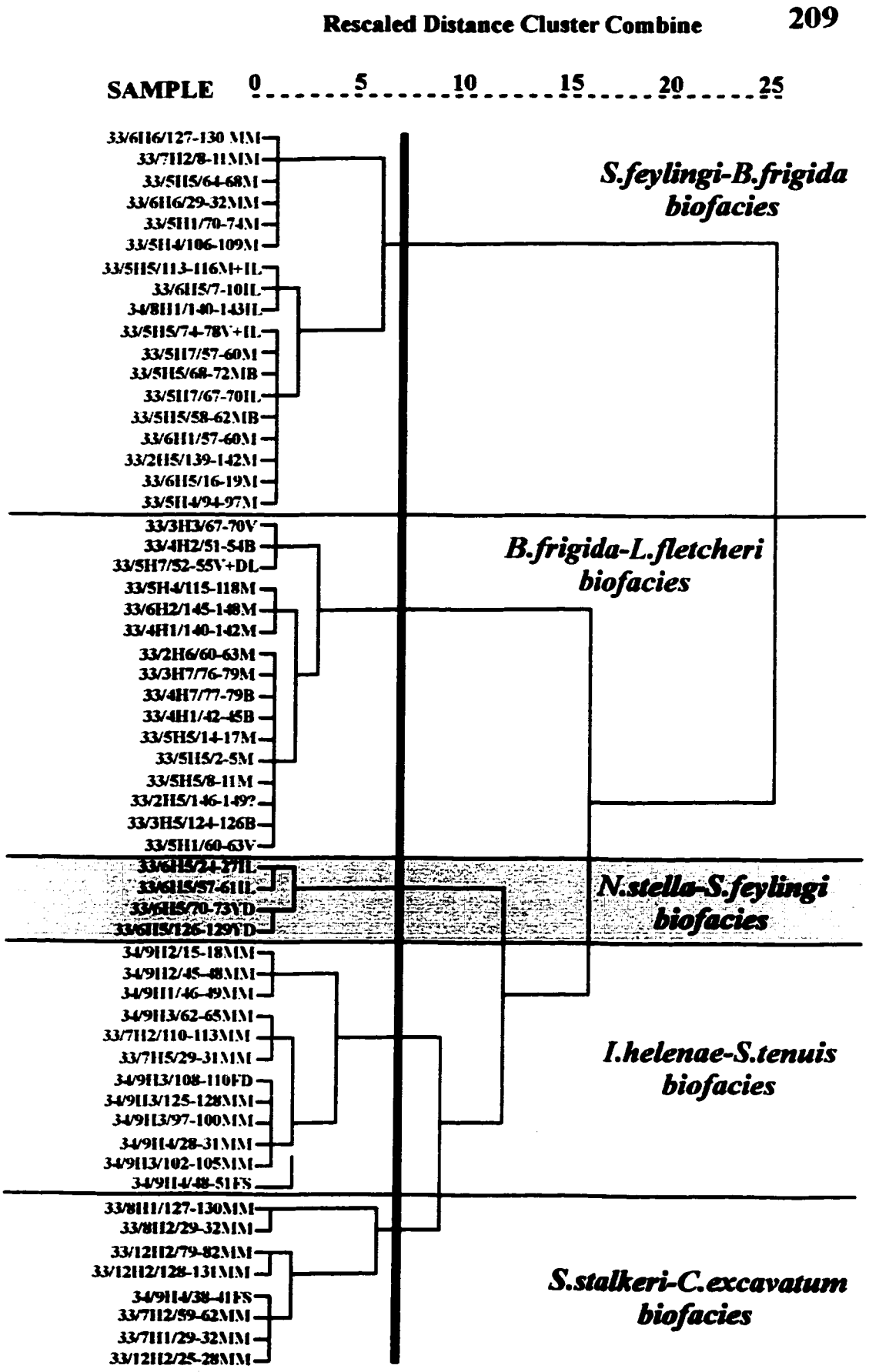
Whiticar, M. J. et al. 1998. Ultra-high resolution climatic, oceanographic, biological and geochemical records in Saanich Inlet, British Columbia. Ocean drilling program Leg 169 S. Second Year annual report. Centre for Earth and Ocean Research, University of Victoria.

Tables:

Figures:

Figure 1. Map of Saanich Inlet showing location of Sites 1033 and 1034




Rescaled Distance Cluster Combine
SAMPLE
0
5
10
15
20
25
33/6H6/127-130 MM
33/7H2/8-11MM
33/5H5/64-68M
33/6H6/29-32MM
33/5H1/70-74M
33/5H4/106-109M
33/5H5/113-116M+IL
33/6H5/7-10IL
34/8H1/140-143IL
33/5H5/74-78V+IL
33/5H7/57-60M
33/5H5/68-72MB
33/5H7/67-70IL
33/5H5/58-62MB
33/6H1/57-60M
33/2H5/139-142M
33/6H5/16-19M
33/5H4/94-97M
S.feylingi-B.frigida biofacies
33/3H3/67-70V
33/4H2/51-54B
33/5H7/52-55V+DL
33/5H4/115-118M
33/6H2/145-148M
33/4H1/140-142M
33/2H6/60-63M
33/3H7/76-79M
33/4H7/77-79B
33/4H1/42-45B
33/5H5/14-17M
33/5H5/2-5M
33/5H5/8-11M
33/2H5/146-149?
33/3H5/124-126B
33/5H1/60-63V
B.frigida-L.fletcheri biofacies
33/6H5/24-27IL
33/6H5/57-61IL
33/6H5/70-73YD
33/6H5/126-129YD
N.stella-S.feylingi biofacies
34/9H2/15-18MM
34/9H2/45-48MM
34/9H1/46-49MM
34/9H3/62-65MM
33/7H2/110-113MM
33/7H5/29-31MM
34/9H3/108-110FD
34/9H3/125-128MM
34/9H3/97-100MM
34/9H4/28-31MM
34/9H3/102-105MM
34/9H4/48-51FS
I.helenae-S.tenuis biofacies
33/8H1/127-130MM
33/8H2/29-32MM
33/12H2/79-82MM
33/12H2/128-131MM
34/9H4/38-41FS
33/7H2/59-62MM
33/7H1/29-32MM
33/12H2/25-28MM
S.stalkeri-C.excavatum biofacies

Core No.	Depth (mbsf)	Lithology	Radiocarbon dates (^{14}C)	Age
1 H	0.0-0.6	Dark gray diatomaceous mud (soupy)	-	Holocene
2H Holocene	0.6-10.1	Dark gray diatomaceous mud (top part not well laminated)	1,407-1,715 yr BP (2H-7, 28 cm, shell)	
3H Holocene	10.1-19.6	Dark gray diatomaceous mud (well laminated with massive beds)	2,892-3,316 yr BP (3H-5, 144 cm, charcoal)	
4H Holocene	19.6-29.1	Gray diatomaceous mud (well laminated with massive beds)	-	
5H Holocene	29.1-38.6	Gray diatomaceous mud with **Mazama Ash Bed**	6,059-6,389 yr BP (5H-1, 8 cm, charcoal) **MAB**: 7,645 yr BP	
6H Holocene	38.6-48.1	Olive gray diatomaceous mud (Indistinctly laminated with massive beds with **Gray Clay Bed**)	8,929-9,226 yr BP (6H-2, 15 cm, shell) 9,078-9,388 yr BP (6H-2, 60 cm, shell) 9,246-9,474 yr BP (6H-2, 90 cm, shell) 10,304-10,879 yr BP (6H-4, 110 cm, shell) 10,952-11,452 yr BP (6H-5, 135 cm, shell) 11,003-11,643 yr BP (6H-5, 141 cm, shell) 11,000-11,687 yr BP (6H-6, 13 cm, shell) 11,668-12,336 yr BP	
Pleistocene			(6H-6, 88 cm, shell)	
7H Pleistocene	48.1-57.6	Gray clay and silty clay, with beds of sand.	-	
8H Pleistocene	57.6-67.1	Gray clay and silty clay, with beds of sand.	-	
9H Pleistocene	67.1-76.6	Gray clay and silty clay, with beds of fine sand.	-	
10H Pleistocene	76.6-86.1	Gray clay and silty clay, with beds of fine sand.	-	
11H Pleistocene	86.1-95.5	Gray clay and silty clay, with beds of fine sand.	-	
12H Pleistocene	95.5-105	Gray clay and silty clay, with beds of fine sand.	-	

Core No.	Depth (mbsf)	Lithology	Radiocarbon dates (^{14}C)	Age
1 H	0.0-4.2	Dark gray diatomaceous mud (disturbed by gas escape)	-	Holocene
2H Holocene	4.2-13.7	Dark gray diatomaceous mud (top part not well laminated)	868-1,199 yr BP (2H-4, 118 cm, shell)	
3H Holocene	13.7-23.2	Dark gray diatomaceous mud (well laminated with massive beds)	1,631-1,923 yr BP (3H-2, 113 cm, wood)	
4H Holocene	23.2-32.7	Gray diatomaceous mud (well laminated with massive beds)	2,781-3,156 yr BP (4H-2, 52 cm, wood) 2,762-3,156 yr BP (4H-2, 108 cm, wood) 4,554-4,977 yr BP (4H-4, 56 cm, wood)	
5H Holocene	32.7-42.2	Gray diatomaceous mud (well laminated with massive beds)	-	
6H Holocene	42.2-51.7	Diatomaceous mud (Indistinctly laminated with massive beds with Gray Clay Bed)	6,303-6,632 yr BP (6H-4, 3 cm, wood) 7,271-7,471 yr BP (6H-CC, 0 cm, shell)	
7H Holocene	51.7-61.2	Diatomaceous mud with **Mazama Ash Bed**	**MAB**: 7,645 yr BP 8,469-8,891 yr B (7H-4, 107 cm, shell) 9,148-9,419 yr BP (7H-6, 129 cm, shell) 11,677-12,377 yr BP (7H-CC, 0 cm, shell)	
Pleistocene				
8H Pleistocene	61.2-70.7	Gray diatomaceous mud, with **Gray Clay Bed**	9,914-10,185 yr BP (8H-2, 57 cm, shell) 10,429-10,927 yr BP (8H-3, 53 cm, shell) 11,098-11,944 yr BP (8H-5, 16 cm, shell) 10,870-11,083 yr BP (8H-5, 134 cm, shell) 11,009-11,662 yr BP (8H-6, 66 cm, shell) 11,702-12,361 yr BP (8H-7, 10 cm, shell)	Holocene
9H Pleistocene	70.7-80.2	Gray clay and silty clay, with beds of fine sand.	13,557-14,067 yr BP (9H-5, 21 cm, shell)	
10H Pleistocene	80.2-89.7	Gray clay and silty clay, with beds of fine sand.	-	
11H Pleistocene	89.7-99.2	Gray clay and silty clay, with beds of fine sand.	-	
12H Pleistocene	99.2-108.7	Gray clay and silty clay, with beds of fine sand.	-	
13H Pleistocene	108.7-118.2	Gray massive silty clay with thin beds of fine sand	-	

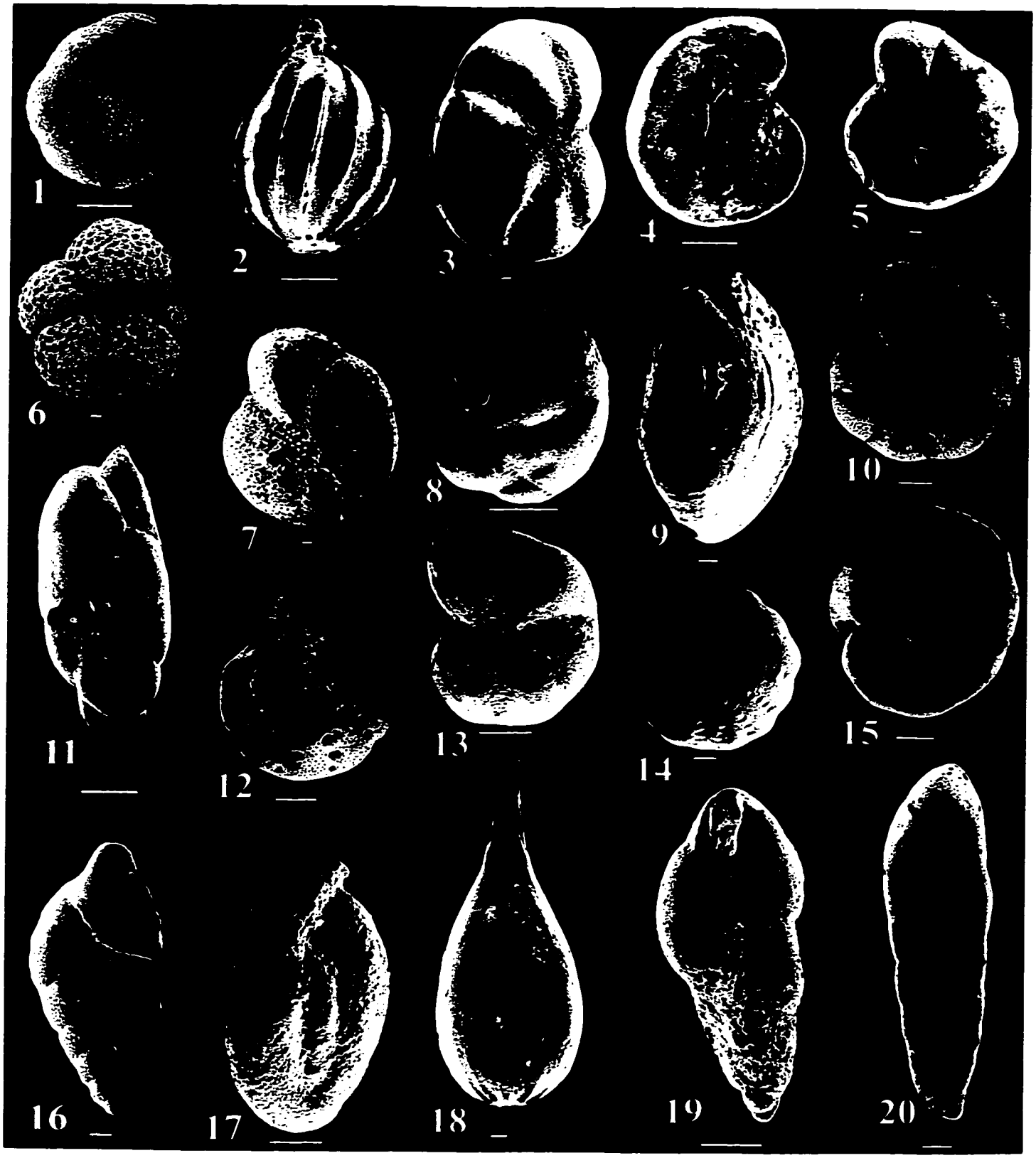
Summary of deglaciation and climatic history of the past 15 k yr BP in southern Vancouver Island.

~3,000 ^{14}C yr BP-Present	Temperatures have been essentially to those of today (Hebda, 1995). Pollen Zone 5 of the late Holocene indicates that modern Neoglacial conditions were established around 3,000 ^{14}C yr BP (Pellatt et al. 1998). Late Holocene climate fluctuations such as the Little Ice Age and Medieval Warm Period are to be studied (Pellatt et al. 1998).
~7,000-3,000 ^{14}C yr BP	Present day oceanographic conditions were established in Saanich Inlet when the sea level rose to its present level in the mid-Holocene (Huntley et al. 1998). Transition from warm, dry climate to moderate, moist conditions (Hebda and Whitlock, 1997). During 6,000 ^{14}C yr BP it was warmer by 1^{0} C than present with comparable precipitation Hebda (1995). Conditions warmer than present persisted until ~5,000 ^{14}C yr BP and cooling occurring at ~4,000 ^{14}C yr BP (Hebda, 1995). Pollen Zone 4 (6,600-ca. 3,000 ^{14}C yr BP) representing mid Holocene represents a period of climatic transition from early Holocene warm/dry conditions to a mild/wet Neoglacial climate with increasing moisture in the late Holocene (Pellatt et al. 1998).
~10,000-7,000 ^{14}C yr BP	Warm and dry interval with severe summer drought conditions, greater than present summer solar radiation and less than present winter solar radiation (Mathewes, 1985). Temperatures were 2^{0} to 4^{0}C warmer than today, with maximum between ~9,000 and 7,500 ^{14}C yr BP. Frequent fires are indicated by abundant charcoal (Cwynar, 1987, Hebda and Whitlock, 1997). Pollen Zone 2 (9910- ca.8680 ^{14}C yr BP) indicates a warm/dry climate in the early Holocene, and Pollen Zone 3 (8680-6600 ^{14}C yr BP) indicates that temperature was higher and precipitation was lower than present throughout most of the early Holocene Pellatt et al. (1998).
~12,000-10,000 ^{14}C yr BP	Soon after 12,500 ^{14}C yr BP, the supply of sediment in Saanich Inlet decreased sharply. The sea level fell relative to land as deglaciation progressed, and by 11,000-10,000 ^{14}C yr BP several tens of meters lower than today. Water depth over the sill was less, consequently circulation was different than now (Huntley et al. 1998). Highly mixed forest assemblages appeared along the coast with no modern equivalent. Thus the nature of climate in this interval is difficult to ascertain (Hebda and Whitlock, 1997). Mathewes (1993) suggested that the unusual combination of species may be related to Younger Dryas cooling. Pollen Zone 1 of Pellatt et al. (1998) representing the Pleistocen-Holocene boundary (ca. 11,000 to 9910 ^{14}C yr BP) indicates a dry, disturbed environment.
~13,000 ^{14}C yr BP	The central Strait of Georgia became deglaciated, and ice in Saanich Inlet retreated to valley outlets, coastal narrows and a bedrock sill at the edge of Satellite Channel. The flux of melt water and sediment into Saanich Inlet was greatest between 13,500 and 12,500 ^{14}C yr BP (Huntley et al. 1998). Climate was cold and dry. (Alley and Chatwin, 1979; Hebda, 1983, 1995)
~14,000 ^{14}C yr BP	Deglaciation began, sea-level in the region were higher relative to land than they are today. The late-glacial marine limit is about 90 m asl in the Saanich Inlet area (Huntley at al. 1998).
~15,000 ^{14}C yr BP	At the climax of Late Wisconsinan Fraser glaciation, this region covered with glacier ice of 1100-1500 m. thickness (Alley and Chatwin, 1979; Huntley et al. 1998).

Photoplate - 1

Bar size: < 0.5 cm = 10 μm; > 0.5 cm = 100 μm

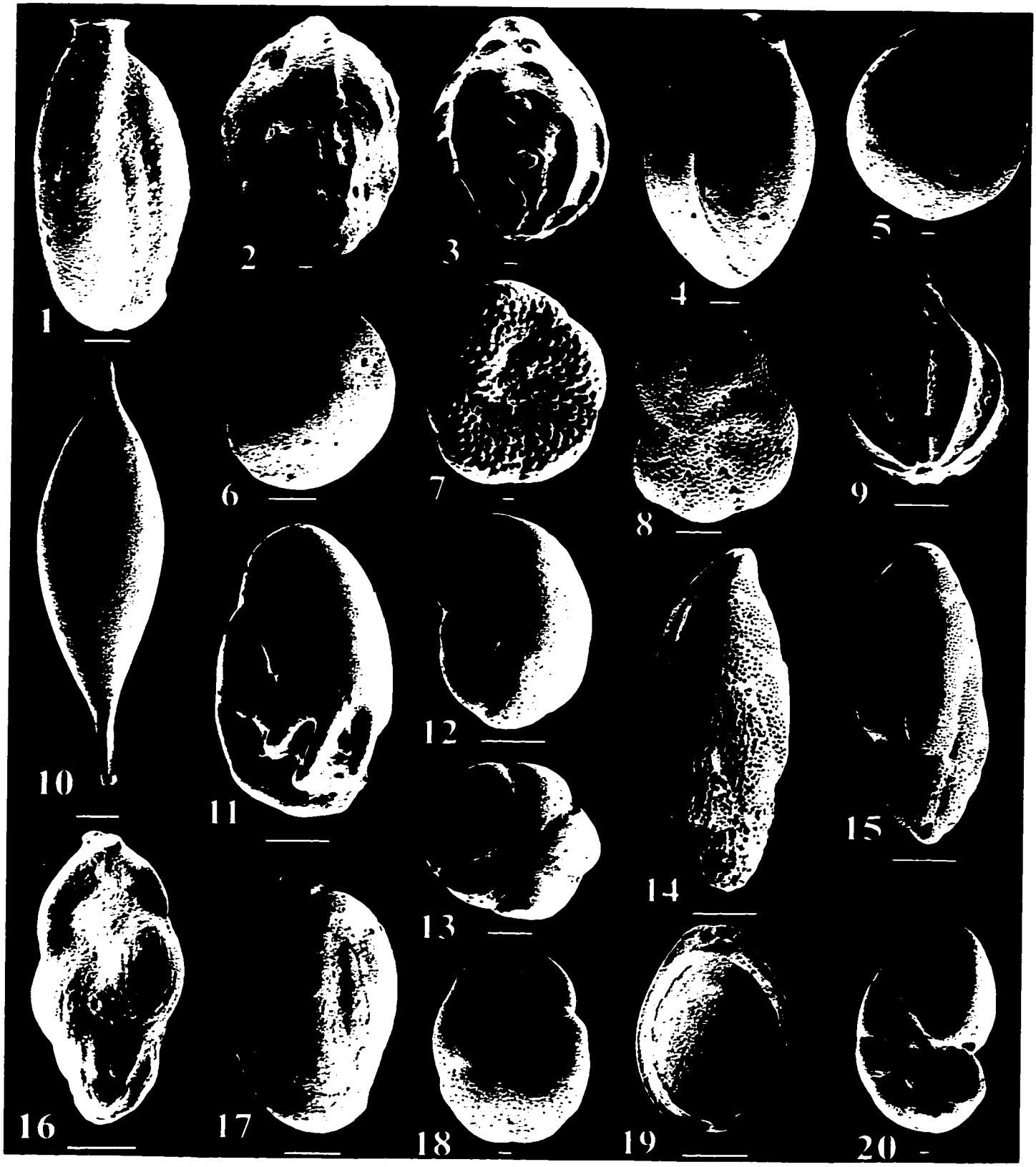
1. *Cribroelphidium excavatum* (Terquem) x 300 side view showing gently curved, incised sutures and pustules along sutures
2. *Homalohedra guntheri* (Earland) x 300 side view showing longitudinal costae and apertural neck
3. *Buccella frigida* (Cushman) x 400 ventral view showing pustule concentration along depressed sutures
4. *Lobatula fletcheri* (Galloway and Wissier) x 300 coarsely perforate spiral view
5. *Lobatula fletcheri* (Galloway and Wissier) x 500 dorsal view with only a few perforations
6. Planktic Foraminifera x 450
7. *Cribroelphidium excavatum* (Terquem) x 400 side view showing gently curved, incised sutures and pustules along sutures
8. *Islandiella helenae* (Feyling-Hansen and Buzas) x 350 side view showing smooth surface and slitted aperture along periphery
9. *Siphonaperta stalkeri* (Loeblich and Tappan) x 80 side view showing terminal aperture
10. *Buccella depressa* (Anderson) x 200 umblical view showing straight sutures and perforated test
11. *Protoglobobulimina elongata* (d'Orbigny) x 300 side view showing distinct elongate test
12. *Cribroelphidium foraminosum* (Cushman) x 200 side view showing perforate surface and fossettes along sutures
13. *Cribroelphidium halladense* (Brotzen) x 300 side view showing pustules concentrated along sutures
14. *Cribroelphidium foraminosum* (Cushman) x 95 side view showing perforate surface and elongate fossettes along sutures
15. *Nonionella stella* (Cushman and Moyer) x 200 dorsal view showing straight to slightly curved sutures
16. *Bolivinellina pacifica* (Cushman and McCulloch) x 250 side view showing elongate test
17. *Spirosigmoilina tenuis* (Czjzek) x 270 side view showing lipped aperture atop elongated neck
18. *Lagena striatocollis* (d'Orbigny) x 400 side view showing poorly developed longitudinal costae restricted to neck and basal region
19. *Stainforthia feylingi* (Knudsen and Seidenkrantz) x 300 side view of elongate specimen showing distinct aperture and perforate surface
20. *Bolivinellina pacifica* (Cushman and McCulloch) x 150 side view showing elongate test


1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

Photoplate - 2

Bar size: < 0.5 cm = 10 μm; > 0.5 cm = 100 μm

1. *Spirosigmoilina tenuis* (Czjzek) x 230 side view showing lipped aperture atop elongated neck
2. *Angulogerina angulosa* (Williamson) x 600 side view showing discontinuous longitudinal costae
3. *Favulina melo* (d'Orbigny) x 500 side view showing curved cross - hatched surface sculpture
4. *Siphonaperta stalkeri* (Loeblich and Tappan) x 140 side view showing terminal aperture with tooth
5. *Fissurina eburnea* (Buchner) x 800 side view showing almost circular profile
6. *Islandiella norcrossi* (Cushman) x 270 side view showing smooth surface and planispiral position of aperture
7. *Cribroelphidium microgranulosum* (Galloway and Wissler) x 500 side view showing granular surface and incised sutures
8. *Cribroelphidium microgranulosum* (Galloway and Wissler) x 250 side view showing granular surface and fossettes along suures
9. *Homalohedra borealis* (Buchner) x 300 side view showing thick longitudinal costae extending from an apical ring to aperture
10. *Hyalinonetrion clavatum* (d'Orbigny) x 190 side view of smooth surfaced, elongate form
11. *Nonionella digitata* (Norvang) x 350 umblical view showing distinctive finger - like projections covering umblical region
12. *Cassidulina reniforme* (Norvang) x 500 edge view showing perforate surface and characteristic flap projecting into apertural opening
13. *Buccella frigida* (Cushman) x 250 ventral view showing pustule concentration along depressed sutures
14. *Buliminella eligantissima* (d'Orbigny) x 350 side view of elongate test with broad apertural opening and perforations all over the surface
15. *Buliminella eligantissima* (d'Orbigny) x 350 test surface showing perforations
16. *Euuvigerina juncea* (Cushman and Todd) x 350
17. *Siphonaperta stalkeri* (Loeblich and Tappan) x 300 side view showing terminal aperture with tooth
18. *Cassidulina reniformae* (Norvang) x 500 edge view showing perforate surface and characteristic flap
19. *Palliolatella frangens* (Buchner) x 350 side view showing development of secondary carina along the margin of each test face
20. *Nonionella labradorica* (Dawson) x 450 apertural view showing characteristic broad flattened apertural face


1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

Foraminiferal data of hole 1033B
(cores 2H to 6H)

Sample No.	Tespecimens	Complete	Broken	C. micrograniulosum	C. excavatum	C. halladense	C. foraminosum	B. frigida	L. fletcheri	S.feylingi	B. elegantissima
2H5/127-130 V	17	6	11	0	5	2	0	5	4	0	0
2H5/139-140 M	186	105	81	0	24	3	0	12	30	84	0
2H5/143-146 ?	41	24	17	0	7	2	0	8	7	10	0
2H5/146-149 ?	56	36	20	0	12	3	0	16	11	4	0
2H6/30-33 V	5	5	0	0	1	0	0	1	1	1	0
2H6/44-47 M	8	6	2	0	3	0	0	2	0	1	2
2H6/49-52 M	12	7	5	0	4	0	0	2	2	1	3
2H6/54-57 M	18	11	7	0	5	0	0	5	2	2	0
2H6/60-63 M	63	45	18	0	11	1	2	19	10	11	0
2H6/65-68 M	25	20	5	0	4	1	3	4	3	5	2
2H6/81-85 V	12	10	2	0	2	1	0	5	2	0	0
3H2/55-58 V	9	5	4	0	3	1	0	3	4	0	0
3H2/63-66 M	29	18	11	0	12	3	0	5	3	0	2
3H2/66-69 M	17	14	3	0	3	2	0	3	2	4	2
3H2/77-80 M	10	7	3	0	2	2	0	1	3	0	0
3H2/83-86 M	31	25	6	0	9	3	0	5	5	1	2
3H2/88-91 M	27	21	6	0	6	3	0	3	10	1	0
3H2/94-97 M	38	27	11	0	10	2	2	15	3	1	0
3H2/98-101 B	45	30	15	0	7	3	1	14	12	3	0
3H2/102-105 V	6	4	2	0	2	0	0	3	1	0	0
3H2/106-108 M	26	17	9	0	7	0	0	5	5	2	6
3H2/110-113 V	18	12	6	0	4	2	0	4	6	0	0
3H3/67-70 V	49	28	21	0	8	2	1	11	3	2	0
3H3/80-83 M	1	1	0	0	0	0	0	0	0	1	0
3H3/87-90 V	16	9	7	0	6	0	0	2	4	0	0
3H3/95-98 M	2	2	0	0	0	0	0	0	0	0	0
3H3/99-102 M	29	20	9	0	8	0	1	8	7	3	0
3H3/103-106 B	36	20	16	0	5	0	1	20	3	1	0
3H3/106-109 B	26	13	13	0	8	1	2	9	2	1	0
3H3/113-116 V	9	5	4	0	4	0	0	3	0	0	0
3H5/10-14 M	33	18	15	0	4	4	3	8	5	3	0
3H5/14-18 M	37	18	19	1	8	1	1	9	14	2	0
3H5/21-24 V	11	4	7	0	3	1	0	3	3	0	0
3H5/60-63 V	17	6	11	0	4	0	0	8	1	0	0
3H5/77-80 M	12	7	5	0	3	0	0	1	1	5	0
3H5/90-93 M	30	12	18	1	10	4	1	5	5	1	0
3H5/102-105 M	27	15	12	0	2	2	0	8	7	4	0
3H5/109-112	29	7	22	0	3	0	0	10	11	1	0
3H5/117-120 M	43	5	38	3	10	2	2	11	10	1	0
3H5/124-126 B	66	21	45	3	10	3	2	18	15	3	0
3H5/127-130	6	0	6	0	3	0	0	1	2	0	0
3H7/11-14 V	19	7	12	0	3	2	0	3	11	0	0
3H7/16-19 M	40	39	1	0	1	1	0	0	0	36	0
3H7/25-28 V	18	5	13	0	2	1	0	4	8	0	0
3H7/42-45 M	4	2	2	0	0	0	0	1	1	2	0
3H7/46-49 M	8	5	3	0	0	0	0	2	2	4	0
3H7/59-62 M	26	9	17	2	5	0	0	4	13	0	0
3H7/63-66 M	28	10	18	0	5	1	1	6	4	9	0
3H7/73-76 M	25	20	5	0	0	1	0	2	1	19	0
3H7/76-79 M	49	22	27	0	7	5	0	12	8	9	0
3H7/79-82 M	19	9	10	0	1	0	0	5	4	4	0
3H7/86-89 V	15	0	15	1	3	1	0	3	6	0	0
4H1/1-4 M	19	7	12	0	2	0	0	3	11	1	0
4H1/6-9 M	24	6	18	0	4	1	1	6	9	1	0
4H1/11-14 M	28	8	20	0	8	0	0	7	13	0	0
4H1/17-20 M	26	11	15	0	4	2	0	6	7	1	0
4H1/23-26 M	34	8	26	0	2	2	0	15	7	0	0
4H1/26-29 M	29	16	13	0	4	0	0	10	4	0	0
4H1/42-45 B	51	19	32	3	8	1	0	13	14	0	0
4H1/45-48 B	13	6	7	0	3	0	0	6	2	1	0
4H1/51-54 V	12	4	8	0	3	0	0	3	1	0	0
4H1/136-139 V	11	3	8	0	1	0	0	5	3	0	0
4H1/140-142 M	69	17	52	0	2	0	0	36	29	0	0
4H1/143-146 V	14	5	9	0	1	0	0	5	1	0	0
4H2/0-4 V	12	6	6	0	0	1	0	2	2	1	0
4H2/4-8 M	7	2	5	0	1	0	0	2	3	0	0
4H2/10-13 V	20	7	13	0	1	3	0	3	7	0	0
4H2/24-27 M	25	4	21	0	1	1	0	12	7	1	0
4H2/30-33 M	33	15	18	0	3	2	0	9	6	5	0
4H2/36-39 M	42	13	29	0	5	0	0	20	8	0	0
4H2/42-45 M	34	12	22	0	6	0	0	8	10	0	0
4H2/47-50 M	39	13	26	0	3	0	0	12	8	1	0
4H2/51-54 B	60	25	35	1	10	1	0	11	16	1	0
4H2/56-59 V	29	21	8	0	1	0	0	2	4	0	0
4H2/109-112 V	18	6	12	0	1	1	0	4	6	1	0
4H2/127-130 M	12	3	9	0	3	0	0	5	0	2	0
4H2/131-134 M	14	7	7	0	1	0	0	2	6	4	0
4H2/135-138 M	38	13	25	5	5	0	0	6	12	0	0
4H2/147-150 V	7	2	5	10	2	0	0	2	2	0	0
4H4/50-53 V	14	5	9	0	1	0	0	5	1	1	0
4H4/61-64 M	9	1	8	0	3	0	0	0	5	0	0
4H4/64-67 B	24	10	14	0	3	2	0	7	5	0	0

Foraminiferal data of hole 1033B
(cores 2H to 6H)

4H4/83-86 V	22	9	13	2	1	0	0	4	4	1	0
4h6/87-90 V	30	16	14	0	1	1	0	7	12	1	0
4H6/92-95 M	23	9	14	0	2	1	0	3	14	1	0
4H6/95-98 B	36	11	25	1	5	2	0	15	11	0	0
4H6/99-102 V	30	16	14	2	1	0	0	6	16	0	0
4H7/63-66 V	35	19	16	2	6	0	0	10	11	0	0
4H7/74-77 M	17	5	12	2	2	0	0	3	8	0	0
4H7/77-79 B	63	26	37	2	8	2	0	16	15	12	0
4H7/80-83 V	17	4	13	0	2	0	0	5	4	0	0
5H1/60-63 V	52	28	24	0	0	0	0	8	20	4	0
5H1/70-74 M	108	108	0	0	3	0	0	3	6	85	0
5H1/74-78 MB	25	16	9	0	0	0	0	9	6	3	0
5H1/86-89 V	20	8	12	0	0	0	0	7	7	0	0
5H2/26-29 DL	45	10	35	0	7	0	0	15	9	0	0
5H2/36-39 IL	1	1	0	0	1	0	0	0	0	0	0
5H2/43-46 IL	2	2	0	1	0	0	0	0	0	0	0
5H2/49-52 IL	2	0	2	0	1	0	0	2	0	0	0
5H2/54-57 IL	3	0	3	0	0	0	0	1	2	0	0
5H2/66-69 DL	1	1	0	0	0	0	0	0	0	0	0
5H3/88-91DL	0	0	0	0	0	0	0	0	0	0	0
5H3/93-96DL	0	0	0	0	0	0	0	0	0	0	0
5H3/104-107 DL	0	0	0	0	0	0	0	0	0	0	0
5H4/63-66 IL	1	1	0	0	0	0	0	0	0	0	0
5H4/82-85 M	0	0	0	0	0	0	0	0	0	0	0
5H4/85-88 M	3	3	0	0	0	0	0	0	0	3	0
5H4/94-97 M	52	30	22	1	2	0	0	10	7	25	0
5H4/106-109 M	51	28	23	0	0	0	0	7	6	34	0
5H4/112-115 M	22	8	14	0	1	0	0	4	1	12	0
5H4/115-118 M	63	21	42	0	6	3	0	31	12	4	0
5H4/126-129 M	28	17	11	0	1	1	0	10	3	9	0
5H4/146-149 M	44	21	23	1	2	3	0	9	17	0	0
5H5/2-5 M	560	392	168	0	135	20	5	200	135	35	0
5H5/8-11 M	1088	979	109	0	208	40	8	392	208	144	0
5H5/14-17 M	736	662	74	0	176	0	0	160	224	64	0
5H5/25-28 ID	33	30	3	0	4	0	0	10	1	12	0
5H5/58-62 V	48	48	0	0	10	2	0	12	0	18	0
5H5/64-68 M	132	110	22	0	6	0	0	24	0	102	0
5H5/68-72 MB	102	90	12	0	20	2	2	6	0	48	0
5H5/74-79 V-IL	114	113	1	0	0	0	0	30	12	48	0
5H5/109-112 DL	24	15	9	0	2	0	0	4	0	1	0
5H5/113-116 M-IL	104	64	40	0	0	0	0	24	0	32	0
5H5/126-129 IL	40	32	8	0	0	0	0	0	8	24	0
5H5/133-136 M	9	5	4	0	2	0	0	3	1	2	0
5H5/139-142 L	16	12	4	0	4	0	0	12	0	0	0
5H7/52-55 V-DL	104	64	40	0	8	0	0	24	0	16	0
5H7/57-60 M	120	112	8	0	0	0	0	32	0	56	0
5H7/67-70 IL	64	56	8	0	0	0	0	8	0	40	0
6H1/53-56 IL	40	40	0	0	0	0	0	8	0	0	0
6H1/57-60 M	152	96	56	0	40	6	0	32	0	56	0
6H1/67-70 IL	10	7	3	0	4	1	1	3	0	0	0
6H1/103-105 C	0	0	0	0	0	0	0	0	0	0	0
6H2/132-135 IL	13	7	6	0	1	0	0	3	1	0	0
6H2/145-148 M	184	64	120	0	20	0	0	92	48	12	0
6H3/9-12 M-B	20	6	14	0	4	0	0	8	1	2	0
6H3/12-15 IL	8	4	4	0	2	0	0	2	1	0	0
6H5/7-10 IL	120	96	24	0	16	0	0	24	0	40	0
6H5/11-14 M	1	1	0	0	0	0	0	0	0	0	0
6H5/16-19 M	69	48	21	0	6	3	0	9	9	27	0
6H5/24-27 IL	176	136	40	8	32	8	0	0	0	40	0
6H5/57-61 IL	180	162	18	0	6	0	0	0	0	78	0
6H5/70-73 YD	528	420	108	4	88	16	8	12	0	0	0
6H5/84-87 YD	0	0	0	0	0	0	0	0	0	0	0
6H5/100-103 YD	1	1	0	0	0	0	0	0	0	1	0
6H5/112-115 YD	0	0	0	0	0	0	0	0	0	0	0
6H5/126-129 M-YD	88	80	8	0	16	0	0	0	0	0	0
6H6/29-32 MM	104	72	32	0	0	0	0	24	0	72	0
6H6/78-81 MM	40	40	0	0	0	0	0	0	0	0	0
6H6/127-130 MM	224	192	32	0	0	0	0	16	0	208	0

Foraminiferal data of hole 1033B
(cores 2H to 6H)

Fissurina spp.	T. nana	T. charlottensis	Planktics	N. stella	B. pacifica	S. agglutinata	Others
0	0	0	0	0	0	0	Agglutinated sphere (? Arcellaceans) (1)
9	12	3	3	0	3	0	Islandiella helenae (3)
1	5	0	1	0	0	0	Arcellaceans (1)
3	7	0	0	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0
0	1	0	2	0	0	0	0
0	5	0	2	1	1	0	0
0	1	0	0	0	2	0	0
2	0	0	0	0	0	0	0
0	0		0	0	0	0	0
0	2	0	2	0	0	0	0
1	0	0	0	0	0	0	0
0	1	0	0	1	0	0	0
0	1	0	2	0	1	0	Islandiella helenae (2)
0	1	0	2	0	0	1	0
0	0	0	5	0	0	0	0
2	0	0	3	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	Arcellaceans (1)
0	0	0	2	0	0	0	0
1	0	0	17	1	1	1	Arcellaceans(1); Rosalina columbiensis (1)
0	0	0	0	0	0	0	0
2	1	0	1	0	0	0	0
0	0	0	0	0	1	0	L.striatocollis (1)
0	0	0	1	0	1	0	0
3	0	0	0	0	2	1	0
3	0	0	0	0	0	0	0
1	0	0	0	0	1	0	0
1	1	0	1	0	2	0	M.fusca (1)
0	1	0	0	0	0	0	0
0	1	0	0	0	0	0	0
2	2	0	0	0	0	0	0
0	0	0	1	0	0	0	Arcellaceans (1)
0	2	0	1	0	0	0	0
2	2	0	0	0	0	0	0
0	0	0	2	1	1	0	0
0	0	0	1	1	1	0	L.striatocollis(1);
2	5	0	0	1	0	0	M.fusca (1); R. columbiensis (3)
0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0
1	1	0	0	0	0	0	0
1	1	0	1	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	2	0	0	0	0	0	0
2	0	0	0	0	0	0	Arcellaceans (1)
0	2	0	0	0	0	0	0
1	3	0	1	0	0	0	M.fusca (1); Arcellaceans (2)
3	2	0	0	0	0	0	0
0	1	0	0	0	0	0	0
0	1	0	0	0	0	0	0
1	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0
1	1	0	4	0	0	0	0
0	0	0	7	0	0	0	M.fusca (1)
1	2	0	8	0	0	0	0
0	4	1	7	0	0	0	0
0	0	0	1	0	0	0	0
1	0		3	0	0	0	M.fusca (1)
0	2	0	0	0	0	0	Buliminella sp. (1)
0	0	0	2	0	0	0	0
1	3	0	3	0	0	0	0
2	3	0	1	0	0	0	0
0	1	0	0	0	0	0	0
0	4	0	2	0	0	0	0
0	1	0	2	0	0	0	0
0	2	0	6	0	0	0	0
0	2	0	5	1	0	0	0
0	5	0	3	1	0	0	0
1	4	0	8	1	0	0	0
0	1	0	19	0	0	0	0
1	1	0	20	0	0	0	0
1	1	0	3	0	0	0	0
0	0	0	1	1	0	0	0
0	1	0	0	0	0	0	0
0	1	0	8	0	0	0	Arcellaceans (1);
0	0	0	0	0	0	0	0
1	1	0	4	0	0	0	0
0	0	0	0	0	0	0	Islandiella helenae (1)
0	3	0	2	1	0	0	Rosalina columbiensis (1)

Foraminiferal data of hole 1033B
(cores 2H to 6H)

0	2	C	8	0	0	0	0
0	2	0	6	0	0	0	0
0	1	C	1	0	0	0	0
0	1	0	1	0	0	0	0
0	0	0	5	0	0	0	0
1	3	0	5	0	0	0	0
0	0	0	2	0	0	0	0
5	0	0	8	0	0	0	0
1	0	0	3	0	0	0	Arcellaceans (1); R. columbiensis (1)
0	0	0	8	0	0	0	Agglutinated spheres (12)
3	0	0	C	0	0	0	Agglutinated spheres (8)
1	2	0	4	0	0	0	0
0	0	0	6	0	0	0	0
0	2	0	12	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	7	0	0	0	4	0	M.fusca (1);
0	0	0	0	0	0	0	M. fusca (4)
1	0	0	0	0	2	0	B. frigida (1)
3	0	0	0	1	0	0	M.fusca (1); Islandiella helenae (2)
0	0	0	0	2	1	0	Islandiella helenae (2)
1	0	0	0	0	1	0	M. fusca (1); Islandiella helenae (2);
0	0	0	0	5	0	5	E. juncea(5);C. reniforme(5);Angulogenina sp. (5);Buliminella (5)
8	8	0	16	16	0	8	Buliminella sp. (32)
0	0	0	48	16	0	0	Homalohedra sp.(16);Buliminella sp. (16); Quinqueloculina sp. (16)
0	0	0	4	0	2	0	0
0	0	0	6	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	18	0	0	0	Euuvigerina ? sp. (6)
0	6	0	18	0	0	0	0
0	0	0	17	0	0	0	0
0	0	0	16	32	0	0	0
0	0	0	8	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	56	0	0	0	0
8	0	0	16	8	0	0	0
0	0	0	16	0	0	0	0
0	0	0	24	0	8	0	0
0	0	0	0	8	8	0	0
0	0	0	0	0	0	0	Favulina melo (1)
0	0	0	0	0	0	0	0
0	0	0	8	0	0	0	0
4	4	0	0	0	0	0	? Buliminella sp.(4)
1	1	0	3	0	0	0	0
0	0	0	3	0	0	0	0
0	8	0	0	24	0	8	0
1	0	0	0	0	0	0	0
3	0	0	3	0	0	0	? Buliminella sp. (9)
0	8	0	0	80	0	0	0
0	0	0	0	96	0	0	0
4	0	0	0	300	0	36	N. digitata (60)
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	72	0	0	0
0	0	0	0	8	0	0	0
0	0	0	0	40	0	0	0
0	0	0	0	0	0	0	0

Foraminiferal dat of Hole 1033B

Sample No.	Tespecimens	Complete	Broken	C. excavatum	C. hatladense	C. foraminosum	S. fricida	L. fletcheri	S.leyingi	B. elegantissima	Fissurina spp.	T. nana	T. charlottensis
2H5/127-130 V	17	6	11	5	2	0	5	4	0	0	0	0	0
2H5/139-140 M	186	105	81	24	3	0	12	30	84	0	9	12	3
2H5/143-146 ?	41	24	17	7	2	0	8	7	10	0	1	5	0
2H5/146-149 ?	56	36	20	12	3	0	16	11	4	0	3	7	0
2H6/30-33 V	5	5	0	1	0	0	1	1	1	0	0	0	0
2H6/44-47 M	8	6	2	3	0	0	2	0	1	2	0	0	0
2H6/49-52 M	12	7	5	4	0	0	2	2	1	3	0	0	0
2H6/54-57 M	18	11	7	5	0	0	5	2	2	0	0	1	0
2H6/60-63 M	63	45	18	11	1	2	19	10	11	0	0	5	0
2H6/65-68 M	25	20	5	4	1	3	4	3	5	2	0	1	0
2H6/81-85 V	12	10	2	2	1	0	5	2	0	0	2	0	0
3H2/55-58 V	9	5	4	3	1	0	3	4	0	0	0	0	
3H2/63-66 M	29	18	11	12	3	0	6	3	0	2	0	2	0
3H2/66-69 M	17	14	3	3	2	0	3	2	4	2	1	0	0
3H2/77-80 M	10	7	3	2	2	0	1	3	0	0	0	1	0
3H2/83-86 M	31	25	6	9	3	0	5	5	1	2	0	1	0
3H2/88-91 M	27	21	6	6	3	0	3	10	1	0	0	1	0
3H2/94-97 M	38	27	11	10	2	2	15	3	1	0	0	0	0
3H2/98-101 B	45	30	15	7	3	1	14	12	3	0	2	0	0
3H2/102-105 V	6	4	2	2	0	0	3	1	0	0	0	0	0
3H2/106-108 M	26	17	9	7	0	0	5	5	2	6	0	0	0
3H2/110-113 V	18	12	6	4	2	0	4	6	0	0	0	0	0
3H3/67-70 V	49	28	21	8	2	1	11	3	2	0	1	0	0
3H3/80-83 M	1	1	0	0	0	0	0	0	1	0	0	0	0
3H3/87-90 V	16	9	7	6	0	0	2	4	0	0	2	1	0
3H3/95-98 M	2	2	0	0	0	0	0	0	0	0	0	0	0
3H3/99-102 M	29	20	9	8	0	1	8	7	3	0	0	0	0
3H3/103-106 B	36	20	16	5	0	1	20	3	1	0	3	0	0
3H3/106-109 B	26	13	13	8	1	2	9	2	1	0	3	0	0
3H3/113-116 V	9	5	4	4	0	0	3	0	0	0	1	0	0
3H5/10-14 M	33	18	15	4	4	3	8	5	3	0	1	1	0
3H5/14-18 M	37	18	19	8	1	1	9	14	2	0	0	1	0
3H5/21-24 V	11	4	7	3	1	0	3	3	0	0	0	1	0
3H5/60-63 V	17	6	11	4	0	0	8	1	0	0	2	2	0
3H5/77-80 M	12	7	5	3	0	0	1	1	5	0	0	0	0
3H5/90-93 M	30	12	18	10	4	1	5	5	1	0	0	2	0
3H5/102-105 M	27	15	12	2	2	0	8	7	4	0	2	2	0
3H5/109-112	29	7	22	3	0	0	10	11	1	0	0	0	0
3H5/117-120 M	43	5	38	10	2	2	11	10	1	0	0	0	0
3H5/124-126 B	66	21	45	10	3	2	18	15	3	0	2	5	0
3H5/127-130	6	0	6	3	0	0	1	2	0	0	0	0	0
3H7/11-14 V	19	7	12	3	2	0	3	11	0	0	0	1	0
3H7/16-19 M	40	39	1	1	1	0	0	0	36	0	1	1	0
3H7/25-28 V	18	5	13	2	1	0	4	8	0	0	1	1	0
3H7/42-45 M	4	2	2	0	0	0	1	1	2	0	0	0	0
3H7/46-49 M	8	5	3	0	0	0	2	2	4	0	0	0	0
3H7/59-62 M	26	9	17	5	0	0	4	13	0	0	0	2	0
3H7/63-66 M	28	10	18	5	1	1	6	4	9	0	2	0	0
3H7/73-76 M	25	20	5	0	1	0	2	1	19	0	0	2	0
3H7/76-79 M	49	22	27	7	5	0	12	8	9	0	1	3	0
3H7/79-82 M	19	9	10	1	0	0	5	4	4	0	3	2	0
3H7/86-89 V	15	0	15	3	1	0	3	6	0	0	0	1	0
4H1/1-4 M	19	7	12	2	0	0	3	11	1	0	0	1	0
4H1/6-9 M	24	6	18	4	1	1	6	9	1	0	1	0	0
4H1/11-14 M	28	8	20	8	0	0	7	13	0	0	0	0	0
4H1/17-20 M	26	11	15	4	2	0	6	7	1	0	1	1	0
4H1/23-26 M	34	8	26	2	2	0	15	7	0	0	0	0	0
4H1/26-29 M	29	16	13	4	0	0	10	4	0	0	1	2	0
4H1/42-45 B	51	19	32	8	1	0	13	14	0	0	0	4	1
4H1/45-48 B	13	6	7	3	0	0	6	2	1	0	0	0	0
4H1/51-54 V	12	4	8	3	0	0	3	1	0	0	1	0	
4H1/136-139 V	11	3	8	1	0	0	5	3	0	0	0	2	0
4H1/140-142 M	69	17	52	2	0	0	36	29	0	0	0	0	0
4H1/143-146 V	14	5	9	1	0	0	5	1	0	0	1	3	0
4H2/0-4 V	12	6	6	0	1	0	2	2	1	0	2	3	0
4H2/4-8 M	7	2	5	1	0	0	2	3	0	0	0	1	0
4H2/10-13 V	20	7	13	1	3	0	3	7	0	0	0	4	0
4H2/24-27 M	25	4	21	1	1	0	12	7	1	0	0	1	0
4H2/30-33 M	33	15	18	3	2	0	9	6	5	0	0	2	0
4H2/36-39 M	42	13	29	5	0	0	20	8	0	0	0	2	0
4H2/42-45 M	34	12	22	6	0	0	8	10	0	0	0	5	0
4H2/47-50 M	39	13	26	3	0	0	12	8	1	0	1	4	0
4H2/51-54 B	60	25	35	10	1	0	11	16	1	0	0	1	0
4H2/56-59 V	29	21	8	1	0	0	2	4	0	0	1	1	0
4H2/109-112 V	18	6	12	1	1	0	4	6	1	0	1	1	0
4H2/127-130 M	12	3	9	3	0	0	5	0	2	0	0	0	0
4H2/131-134 M	14	7	7	1	0	0	2	6	4	0	0	1	0
4H2/135-138 M	38	13	25	5	0	0	6	12	0	0	0	1	0
4H2/147-150 V	7	2	5	2	0	0	2	2	0	0	0	0	0
4H4/50-53 V	14	5	9	1	0	0	5	1	1	0	1	1	0
4H4/61-64 M	9	1	8	3	0	0	0	5	0	0	0	0	0
4H4/64-67 B	24	10	14	3	2	0	7	5	0	0	0	3	0
4H4/83-86 V	22	9	13	1	0	0	4	4	1	0	0	2	0
4H6/87-90 V	30	16	14	1	1	0	7	12	1	0	0	2	0
4H6/92-95 M	23	9	14	2	1	0	3	14	1	0	0	1	0
4H6/95-98 B	36	11	25	5	2	0	15	11	0	0	0	1	0
4H6/99-102 V	30	16	14	1	0	0	6	16	0	0	0	0	0

Foraminiferal dat cf Hole 1033B

4H7/63-66 V	35	19	16	6	0	0	10	11	0	0	1	3	0
4H7/74-77 M	17	5	12	2	0	0	3	8	0	0	0	0	0
4H7/77-79 B	63	26	37	8	2	0	16	15	12	0	5	0	0
4H7/80-83 V	17	4	13	2	0	0	5	4	0	0	1	0	0
5H1/60-63 V	52	28	24	0	0	0	8	20	4	0	0	0	0
5H1/70-74 M	108	108	0	3	0	0	3	6	85	0	3	0	0
5H1/74-78 MB	25	16	9	0	0	0	9	6	3	0	1	2	0
5H1/86-89 V	20	8	12	0	0	0	7	7	0	0	0	0	0
5H2/26-29 DL	45	10	35	7	0	0	15	9	0	0	0	2	0
5H2/36-39 IL	1	1	0	1	0	0	0	0	0	0	0	0	0
5H2/43-46 IL	2	2	0	0	0	0	0	0	0	0	0	0	0
5H2/49-52 IL	2	0	2	1	0	0	2	0	0	0	0	0	0
5H2/54-57 IL	3	0	3	0	0	0	1	2	0	0	0	0	0
5H2/66-69 DL	1	1	0	0	0	0	0	0	0	0	1	0	0
5H3/88-91DL	0	0	0	0	0	0	0	0	0	0	0	0	0
5H3/93-96DL	0	0	0	0	0	0	0	0	0	0	0	0	0
5H3/104-107 DL	0	0	0	0	0	0	0	0	0	0	0	0	0
5H4/63-66 IL	1	1	0	0	0	0	0	0	0	0	0	0	0
5H4/82-85 M	0	0	0	0	0	0	0	0	0	0	0	0	0
5H4/85-88 M	3	3	0	0	0	0	0	0	3	0	0	0	0
5H4/94-97 M	52	30	22	2	0	0	10	7	26	0	0	7	0
5H4/106-109 M	51	28	23	0	0	0	7	6	34	0	0	0	0
5H4/112-115 M	22	8	14	1	0	0	4	1	12	0	1	0	0
5H4/115-118 M	63	21	42	6	3	0	31	12	4	0	3	0	0
5H4/126-129 M	28	17	11	1	1	0	10	3	9	0	0	0	0
5H4/146-149 M	44	21	23	2	3	0	9	17	0	0	1	0	0
5H5/2-5 M	560	392	168	135	20	5	200	135	35	0	0	0	0
5H5/8-11 M	1088	979	109	208	40	8	392	208	144	0	8	8	0
5H5/14-17 M	736	662	74	176	0	0	160	224	64	0	0	0	0
5H5/25-28 ID	33	30	3	4	0	0	10	1	12	0	0	0	0
5H5/58-62 V	48	48	0	10	2	0	12	0	18	0	0	0	0
5H5/64-68 M	132	110	22	6	0	0	24	0	102	0	0	0	0
5H5/68-72 MB	102	90	12	20	2	2	6	0	48	0	0	0	0
5H5/74-78 V-IL	114	113	1	0	0	0	30	12	48	0	0	6	0
5H5/109-112 DL	24	15	9	2	0	0	4	0	1	0	0	0	0
5H5/113-116 M-IL	104	64	40	0	0	0	24	0	32	0	0	0	0
5H5/126-129 IL	40	32	8	0	0	0	0	8	24	0	0	0	0
5H5/133-136 M	9	5	4	2	0	0	3	1	2	0	0	0	0
5H5/139-142 L	16	12	4	4	0	0	12	0	0	0	0	0	0
5H7/52-55 V-DL	104	64	40	8	0	0	24	0	16	0	0	0	0
5H7/57-60 M	120	112	8	0	0	0	32	0	56	0	8	0	0
5H7/67-70 IL	64	56	8	0	0	0	8	0	40	0	0	0	0
6H1/53-56 IL	40	40	0	0	0	0	8	0	0	0	0	0	0
6H1/57-60 M	152	96	56	40	6	0	32	0	56	0	0	0	0
6H1/67-70 IL	10	7	3	4	1	1	3	0	0	0	0	0	0
6H1/103-105 C	0	0	0	0	0	0	0	0	0	0	0	0	0
6H2/132-135 IL	13	7	6	1	0	0	3	1	0	0	0	0	0
6H2/145-148 M	184	64	120	20	0	0	92	46	12	0	4	4	0
6H3/9-12 M-B	20	6	14	4	0	0	8	1	2	0	1	1	0
6H3/12-15 IL	8	4	4	2	0	0	2	1	0	0	0	0	0
6H5/7-10 IL	120	96	24	16	0	0	24	0	40	0	0	8	0
6H5/11-14 M	1	1	0	0	0	0	0	0	0	0	1	0	0
6H5/16-19 M	69	48	21	6	3	0	9	9	27	0	3	0	0
6H5/24-27 IL	176	136	40	32	8	0	0	0	40	0	0	8	0
6H5/57-61 IL	180	162	18	6	0	0	0	0	78	0	0	0	0
6H5/70-73 YD	528	420	108	88	16	8	12	0	0	0	4	0	0
6H5/84-87 YD	0	0	0	0	0	0	0	0	0	0	0	0	0
6H5/100-103 YD	1	1	0	0	0	0	0	0	1	0	0	0	0
6H5/112-115 YD	0	0	0	0	0	0	0	0	0	0	0	0	0
6H5/126-129 M-YD	88	80	8	16	0	0	0	0	0	0	0	0	0
6H6/29-32 MM	104	72	32	0	0	0	24	0	72	0	0	0	0
6H6/78-81 MM	40	40	0	0	0	0	0	0	0	0	0	0	0
6H6/127-130 MM	224	192	32	0	0	0	16	0	208	0	0	0	0
7H1/29-32 MM	1760	1322	440	1176	64	40	128	8	288	0	0	8	0
7H1/78-81 MM	17	13	4	6	2	1	2	0	3	0	0	0	0
7H1/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
7H2/8-11 MM	219	219	0	3	0	0	0	0	213	0	0	0	0
7H2/59-62 MM	262	32	230	140	16	4	4	0	2	0	0	0	0
7H2/110-113 MM	134	36	98	26	4	0	10	4	16	0	0	0	0
7H3/29-32 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
7H3/78-81 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
7H3/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
7H4/29-32 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
7H4/78-81 MM	8	5	3	1	0	0	2	2	0	0	0	0	0
7H4/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
7H5/29-31 MM	237	132	105	39	12	3	12	0	0	0	0	33	0
7H5/78-81 MM	4	4	0	0	0	0	0	0	0	0	0	0	0
7H5/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
7H6/29-32 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
7H6/78-81 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
7H6/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
8H1/29-32 MM	2	2	0	0	0	0	0	0	0	0	0	0	0
8H1/77-80 MM	25	16	9	0	0	0	0	0	0	0	0	0	0
8H1/127-130 MM	57	44	13	4	1	1	0	0	0	0	0	0	0
8H2/29-32 MM	137	95	42	27	8	0	0	0	0	0	0	0	0
8H2/76-79 MM	8	8	0	6	0	0	0	0	0	0	0	0	0
8H2/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
8H3/29-32 MM	1	1	0	1	0	0	0	0	0	0	0	0	0
8H3/77-80 MM	1	1	0	0	0	0	0	0	0	0	0	0	0

Foraminiferal dat of Hole 1033B

8H3/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
8H4/29-32 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
8H4/77-80 MM	2	2	0	2	0	0	0	0	0	0	0	0	0
8H4/117-120 MM	11	9	2	5	3	1	0	0	0	0	0	0	0
8H5/29-32 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
8H5/77-80 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
8H5/126-129 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
8H6/29-32 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
8H6/75-77 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
8H6/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H1/25-28 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H1/77-80 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H1/130-133 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H2/29-32 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H2/77-80 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H2/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H3/29-32 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H3/77-80 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H3/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H4/13-16 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H4/67-70 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H4/145-148 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H5/25-28 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H5/77-80 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H5/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H6/25-28 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H6/ 77-80 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
9H6/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H1/25-28 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H1/77-80 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H1/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H2/25-28 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H2/78-81 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H2/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H3/23-26 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H3/78-81 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H3/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H4/25-28 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H4/78-81 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H4/145-148 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H5/25-28 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H5/78-81 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H5/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H6/25-28 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H6/77-80 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
10H6/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
11H1/25-28 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
11H1/78-81 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
11H1/127-130 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
11H2/25-28 MM	3	2	1	1	0	0	0	0	0	0	0	0	0
11H2/78-81 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
11H2/126-129 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
11H3/16-19 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
11H3/77-80 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
11H3/126-129 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
11H4/25-28 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
11H4/77-80 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
11H4/147-150 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
11H5/17-20 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
11H5/77-80 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
11H5/126-129 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
11H6/10-13 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
11H6/46-49 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
12H1/25-28 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
12H1/79-82 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
12H1/134-137 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
12H2/25-28 MM	100	88	12	56	0	12	0	0	0	0	0	0	0
12H2/79-82 MM	290	230	60	120	65	10	0	0	0	0	0	0	0
12H2/128-131 MM	90	75	15	30	27	12	0	0	0	0	0	0	0
12H3/31-35 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
12H3/79-82 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
12H3/140-143 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
12H4/25-28 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
12H4/79-82 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
12H4/145-148 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
12H5/25-28 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
12H5/79-82 MM	0	0	0	0	0	0	0	0	0	0	0	0	0
12H5/130-133 MM	0	0	0	0	0	0	0	0	0	0	0	0	0

Foraminiferal dat of Hole 1033B

Planktics	N. stella	B. pacifica	S. stalker	Others
0	0	0	0	Agglutinated sphera (? Arcellaceans) (1)
3	0	3	0	Islandiella helenae (3)
0	0	0	0	Arcellaceans (1)
0	0	0	0	0
0	1	0	0	0
1	0	0	0	0
0	0	0	0	0
2	0	0	0	0
2	1	1	0	0
0	0	2	0	0
0	0	0	0	0
0	0	0	0	0
2	0	0	0	0
0	0	0	0	0
0	1	0	0	0
2	0	1	0	Islandiella helenae (2)
2	0	0	1	0
5	0	0	0	0
3	0	0	0	0
0	0	0	0	0
0	0	0	0	Arcellaceans (1)
2	0	0	0	0
17	1	1	1	Arcellaceans(1); Rosalina columbiensis (1)
0	0	0	0	0
1	0	0	0	0
0	0	1	0	L.striatocollis (1)
1	0	1	0	0
0	0	2	1	0
0	0	0	0	0
0	0	1	0	0
1	0	2	0	M.fusca (1)
0	0	0	0	C. micrograniulosum (1)
0	0	0	0	0
0	0	0	0	0
1	0	0	0	Arcellaceans (1)
1	0	0	0	C. micrograniulosum (1)
0	0	0	0	0
2	1	1	0	0
1	1	1	0	L.striatocollis(1); C micrograniulosum (3)
0	1	0	0	M.fusca (1); C. micrograniulosum (3); R. columbiensis (3)
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
1	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	C. micrograniulosum (2)
0	0	0	0	Arcellaceans (1)
0	0	0	0	0
1	0	0	0	M.fusca (1); Arcellaceans (2)
0	0	0	0	0
0	0	0	0	C. micrograniulosum
0	0	0	0	0
1	0	0	0	0
0	0	0	0	0
4	0	0	0	0
7	0	0	0	M.fusca (1)
8	0	0	0	0
7	0	0	0	C. micrograniulosum
1	0	0	0	0
3	0	0	0	M.fusca (1)
0	0	0	0	Buliminella sp. (1)
2	0	0	0	0
3	0	0	0	0
1	0	0	0	0
0	0	0	0	0
2	0	0	0	0
2	0	0	0	0
6	0	0	0	0
5	1	0	0	0
3	1	0	0	0
8	1	0	0	0
19	0	0	0	C. micrograniulosum (1)
20	0	0	0	0
3	0	0	0	0
1	1	0	0	0
0	0	0	0	0
8	0	0	0	Arcellaceans (1); C. micrograniulosum (5)
0	0	0	0	C. micrograniulosum (10
4	0	0	0	0
0	0	0	0	Islandiella helenae (1)
2	1	0	0	Rosalina columbiensis (1)
8	0	0	0	C. micrograniulosum (2)
6	0	0	0	0
1	0	0	0	0
1	0	0	0	C. micrograniulosum (1)
5	0	0	0	C. micrograniulosum (2)

Foraminiferal dat of Hole 10338

5	0	0	0	C. microgranulosum (2)
2	0	0	0	C. microgranulosum (2)
8	0	0	0	C. microgranulosum (2)
3	0	0	0	Arcellaceans (1); R. columbiensis (1)
8	0	0	0	Agglutinated spheres (12)
0	0	0	0	Agglutinated spheres (8)
4	0	0	0	0
6	0	0	0	0
12	0	0	0	0
0	0	0	0	0
1	0	0	0	C. microgranulosum (1)
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
1	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	4	0	M.fusca (1); C. microgranulosum (1)
0	0	0	0	M. fusca (4)
0	0	2	0	B. frigida (1)
0	1	0	0	M.fusca (1), Islandiella helenae (2)
0	2	1	0	Islandiella helenae (2)
0	0	1	0	M. fusca (1); Islandiella helenae (2); C. microgranulosum (1)
0	5	0	5	E. juncea(5);C. reniforme(5);Angulogenna sp. (5);Bulimnella (5)
16	16	0	8	Bulimnella sp. (32)
48	16	0	0	Homalohedra sp.(16);Bulimnella sp. (16); Quinqueloculina sp. (16)
4	0	2	0	0
6	0	0	0	0
0	0	0	0	0
18	0	0	0	Euuvigerina ? sp. (6)
18	0	0	0	0
17	0	0	0	0
16	32	0	0	0
8	0	0	0	0
1	0	0	0	0
0	0	0	0	0
56	0	0	0	0
16	8	0	0	0
16	0	0	0	0
24	0	8	0	0
0	8	8	0	0
0	0	0	0	Favulina melo (1)
0	0	0	0	0
8	0	0	0	0
0	0	0	0	? Bulimnella sp.(4)
3	0	0	0	0
3	0	0	0	0
0	24	0	8	0
0	0	0	0	0
3	0	0	0	? Bulimnella sp. (9)
0	80	0	0	C. microgranulosum (8)
0	96	0	0	0
0	300	0	36	N. digitata (60); C. microgranulosum (4)
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	72	0	0	0
0	8	0	0	0
0	40	0	0	0
0	0	0	0	0
0	0	0	0	C. microgranulosum (48)
0	1	0	3	0
0	0	0	0	0
0	0	0	3	0
0	0	0	1	Bulimnella sp. (2); Islandiella helenae (58); C. microgranulosum (20)
0	4	0	12	Islandiella helenae (36); I. norcossi (22)
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	Islandiella norcossi (2); Bulimnella sp. (1)
0	0	0	0	0
0	0	3	0	Rosalina sp.(15);I.narcossi (36);Foram-B (3);Foram-C (3);Foram-D (9)
0	0	0	1	N. digitata (2); Arcellaceans (1)
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	2	0
0	0	0	19	N. digitata (5); Astrononion galloway (1)
0	0	0	39	Rosalina sp. (3); N. digitata (9)
0	3	0	75	N. digitata (8); Hyalinonetron clavatum (2);Rosalina sp. (14)
0	0	0	0	Rosalina sp.(2)
0	0	0	0	0
0	0	0	0	0
0	0	0	0	Astrononion galloway (1)

Foraminiferal dat of Hole 1033B

0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	2	0
0	0	0	0	0
0	0	0	0	[illegible]
0	0	0	0	[illegible]
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	Islandiella helenae (2)
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	20	I. helenae (4);Cassidulina reniformae (4);Foram-x (4)
0	0	0	60	I. helenae (30); C. reniformae (5)
0	0	0	12	I. helenae (9)
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0

Foraminiferal data of Hole 1034B

Sample No.	T#specimens	Complete	Broken	C. excavatum	C. halladense	C. foraminosum	B. frigida	L. fletcheri	S.feylingi	B. eligantissima
2H6/64-67 V	0	0	0	0	0	0	0	0	0	0
2H6/75-78 M	3	2	1	0	0	0	1	1	0	0
2H6/78-81 M	2	2	0	0	0	0	1	1	0	0
2H6/81-84 M	3	2	1	0	0	0	0	0	1	0
2H6/84-87 M	9	1	8	5	0	0	2	0	0	0
2H6/89-92 V	0	0	0	0	0	0	0	0	0	0
3H1/20-23 V	2	2	0	0	0	0	2	0	0	0
3H1/136-139 V	2	2	0	1	0	0	1	0	0	0
3H1/142-145 M	0	0	0	0	0	0	0	0	0	0
3H1/145-148 M	3	0	3	0	0	0	0	3	0	0
3H2/36-39 V	9	0	9	2	0	0	3	4	0	0
3H2/63-66 V	4	1	3	0	0	0	1	0	0	0
3H2/124-127 V	8	0	8	0	0	0	5	3	0	0
3H3/20-23 V	7	5	2	3	0	0	0	4	0	0
3H4/52-55 V	10	7	3	3	0	0	4	3	0	0
3H5/127-130 M	11	3	8	1	0	0	6	4	4	0
3H5/130-133 V	5	4	1	0	0	0	2	3	0	0
3H5/138-141 M	14	1	13	1	0	0	6	3	0	0
3H5/141-144 M	5	0	5	0	0	0	4	0	0	0
3H5/144-147 M	12	2	10	0	0	1	6	1	0	0
3H5/147-150 M	2	0	2	0	0	0	0	1	0	0
3H6/89-92 V	0	0	0	0	0	0	0	0	0	0
3H7/23-26 V	4	1	3	0	0	1	2	1	0	0
3H7/29-32 M	1	0	1	1	0	0	0	0	0	0
3H7/35-38 M	6	0	6	2	1	1	2	0	0	0
3H7/43-46 M	7	0	7	0	1	1	1	4	0	0
3H7/50-63 V	5	3	2	1	0	0	1	1	0	1
4H2/19-22 V	4	0	4	2	0	0	1	1	0	0
4H2/28-31 V	6	0	6	1	0	0	1	4	0	0
4H2/33-36 M	5	0	5	2	0	0	3	0	0	0
4H2/36-39 M	3	0	3	1	0	0	2	0	0	0
4H2/45-48 M	5	0	5	3	0	0	1	0	0	0
4H2/133-136 V	2	0	2	0	0	0	2	0	0	0
4H2/135-138 M	5	1	4	3	0	0	2	0	0	0
4h2/145-148 M	0	0	0	0	0	0	0	0	0	0
4H6/35-38 V	1	0	1	0	0	0	1	0	0	0
4h6/54-57 V	0	0	0	0	0	0	0	0	0	0
4H6/58-61 M	4	0	4	1	0	0	1	1	0	0
4H6/62-65 V	0	0	0	0	0	0	0	0	0	0
4H6/87-90 V	2	0	2	0	0	0	2	0	0	0
4H6/134-137	9	1	8	0	0	0	2	4	0	0
4H7/68-71 V	1	1	0	0	0	0	0	0	0	0
4H7/72-75 M	7	0	7	2	0	0	2	0	0	0
4H7/75-78 M	18	4	14	3	6	2	2	0	0	0
4H7/78-81 M	5	0	5	0	0	0	2	3	0	0
4H7/84-87 V	4	2	2	0	0	0	1	0	0	0
5H1/1-4 ML ?	0	0	0	0	0	0	0	0	0	0
5H1/5-8 ML ?	0	0	0	0	0	0	0	0	0	0
5H1/9-12 V	0	0	0	0	0	0	0	0	0	0
5H3/44-47 V	11	4	7	0	0	0	2	5	0	0
5H3/49-52 M	9	1	8	1	1	0	2	0	0	0
5H3/54-57 M	3	0	3	2	0	0	0	0	0	0
5H3/72-75 M	5	0	5	2	0	0	2	1	0	0
5H3/75-78 M	8	2	6	2	0	0	1	3	0	0
5H3/82-85 V	10	4	6	0	1	0	1	5	0	0
5H7/1-4 M	9	2	7	1	1	0	2	3	0	0
5H7/5-8 V	4	3	1	0	0	0	0	0	0	0
6H1/95-98 V	3	0	3	0	0	0	2	1	0	0
6H2/56-59 V	5	1	4	2	0	0	0	3	0	0
6H2/83-86 V	7	1	6	2	0	0	2	2	0	0
6H2/89-92 M	5	0	5	2	0	0	0	3	0	0
6H2/107-110 V	1	0	1	0	0	0	0	1	0	0
6H4/87-90 V	3	0	3	0	0	0	2	1	0	0
6H7/5-8 M	3	0	3	1	0	0	2	0	0	0
6H7/10-13 V	5	1	4	0	0	0	2	2	0	0
7H1/50-53 V	6	1	5	0	0	0	1	0	0	0
7H1/104-107 IL	0	0	0	0	0	0	0	0	0	0
7H1/127-130 IL	0	0	0	0	0	0	0	0	0	0
7H2/17-20 IL	0	0	0	0	0	0	0	0	0	0
7H2/90-93 IL	0	0	0	0	0	0	0	0	0	0
7H2/133-136 IL	9	0	9	0	2	0	3	0	0	0
7H3/18-21 IL	0	0	0	0	0	0	0	0	0	0
7H3/57-60 IL	5	1	4	0	0	0	2	3	0	0
7H3/128-131 IL	0	0	0	0	0	0	0	0	0	0
7H4/8-11 IL	0	0	0	0	0	0	0	0	0	0

Foraminiferal data of Hole 1034B

7H4/35-38 IL	0	0	0	0	0	0	0	0	0	0
7H4/126-129 IL	6	0	6	3	0	0	3	0	0	0
7H5/3-6 IL	0	0	0	0	0	0	0	0	0	0
7H5/108-111 IL	3	0	3	1	0	0	0	2	0	0
7H6/145-148 IL	2	2	0	0	0	0	0	0	0	0
7H7/6-9 IL	0	0	0	0	0	0	0	0	0	0
7H7/65-68 IL	0	0	0	0	0	0	0	0	0	0
8H1/140-143 IL	604	460	144	0	0	0	72	0	156	148
8H2/11-14 V	4	0	4	4	0	0	0	0	0	0
8H6/20-23 ID	0	0	0	0	0	0	0	0	0	0
8H6/81-84 ID	0	0	0	0	0	0	0	0	0	0
8H6/125-128 ID	0	0	0	0	0	0	0	0	0	0
9H1/46-49 MM	64	20	44	6	0	0	0	0	0	0
9H1/122-125 MM	4	3	1	4	0	0	0	0	0	0
9H2/15-18 MM	58	32	13	10	0	0	0	0	0	0
9H2/45-48 MM	60	24	36	9	0	0	0	0	6	0
9H2/86-89 MM	0	0	0	0	0	0	0	0	0	0
9H3/8-11 MM	0	0	0	0	0	0	0	0	0	0
9H3/25-28 MM	2	0	2	0	0	0	0	0	0	0
9H3/31-34 MM	10	4	6	4	0	0	0	0	0	0
9H3/35-38 MM	16	8	8	0	0	0	0	0	0	0
9H3/62-65 MM	249	99	150	48	18	51	0	0	0	0
9H3/97-100 MM	94	34	30	4	0	0	0	0	0	0
9H2/102-105 MM	56	6	50	0	0	0	0	0	0	0
9H3/108-110 FD	188	36	152	16	8	12	0	0	0	0
9H3/125-128 MM	132	32	100	22	0	0	0	0	0	0
9H4/28-31 MM	63	18	45	9	0	0	0	0	0	0
9H4/34-37 MM	0	0	0	0	0	0	0	0	0	0
9H4/38-41 FS	80	48	32	40	0	0	0	0	16	0
9H4/48-51 FS	48	0	48	16	0	0	0	0	0	0
9H4/52-55 FS	16	0	16	0	0	0	0	0	0	0
9H4/118-121 MM	0	0	0	0	0	0	0	0	0	0
10H5/11-14 MM	0	0	0	0	0	0	0	0	0	0
10H5/43-46 MM	0	0	0	0	0	0	0	0	0	0
11H3/11-14 MM	0	0	0	0	0	0	0	0	0	0
11H3/50-53 MM	0	0	0	0	0	0	0	0	0	0
11H3/95-98 MM	0	0	0	0	0	0	0	0	0	0
11H3/134-137 MM	0	0	0	0	0	0	0	0	0	0
11H4/13-16 MM	0	0	0	0	0	0	0	0	0	0
11H4/50-53 MM	0	0	0	0	0	0	0	0	0	0
11H4/93-96 MM	0	0	0	0	0	0	0	0	0	0
11H4/127-130 MM	0	0	0	0	0	0	0	0	0	0
11H5/13-16 MM	0	0	0	0	0	0	0	0	0	0
11H5/48-51 MM	0	0	0	0	0	0	0	0	0	0
11H5/89-92 MM	0	0	0	0	0	0	0	0	0	0
11H5/127-130 MM	0	0	0	0	0	0	0	0	0	0
11H6/10-13 MM	0	0	0	0	0	0	0	0	0	0
11H6/33-36 MM	0	0	0	0	0	0	0	0	0	0
11H6/48-51 MM	2	2	0	2	0	0	0	0	0	0
11H6/93-96 MM	0	0	0	0	0	0	0	0	0	0
11H6/133-136 MM	0	0	0	0	0	0	0	0	0	0
11H7/33-36 MM	0	0	0	0	0	0	0	0	0	0
12H1/11-14 MM	0	0	0	0	0	0	0	0	0	0
12H1/49-52 MM	0	0	0	0	0	0	0	0	0	0
12H1/91-94 MM	0	0	0	0	0	0	0	0	0	0
12H1/139-142 MM	0	0	0	0	0	0	0	0	0	0
12H2/9-12 MM	0	0	0	0	0	0	0	0	0	0
12H2/50-53 MM	0	0	0	0	0	0	0	0	0	0
12H2/91-94 MM	0	0	0	0	0	0	0	0	0	0
12H2/125-128 MM	0	0	0	0	0	0	0	0	0	0
12H3/10-13 MM	0	0	0	0	0	0	0	0	0	0
12H3/49-52 MM	0	0	0	0	0	0	0	0	0	0
12H3/93-96 MM	0	0	0	0	0	0	0	0	0	0
12H3/133-136 MM	0	0	0	0	0	0	0	0	0	0
12H4/10-13 MM	0	0	0	0	0	0	0	0	0	0
12H4/46-49 MM	0	0	0	0	0	0	0	0	0	0
12H4/115-118 MM	0	0	0	0	0	0	0	0	0	0
12H5/9-12 MM	0	0	0	0	0	0	0	0	0	0
12H5/49-52 MM	0	0	0	0	0	0	0	0	0	0
12H5/93-96 MM	0	0	0	0	0	0	0	0	0	0
12H5/132-135 MM	0	0	0	0	0	0	0	0	0	0
12H6/10-13 MM	0	0	0	0	0	0	0	0	0	0
12H6/58-61 MM	0	0	0	0	0	0	0	0	0	0
13H1/9-12 MM	0	0	0	0	0	0	0	0	0	0
13H1/48-51 MM	0	0	0	0	0	0	0	0	0	0
13H1/90-93 MM	0	0	0	0	0	0	0	0	0	0
13H1/135-138 MM	0	0	0	0	0	0	0	0	0	0

Foraminiferal data of Hole 1034B

13H2/10-13 MM	0	0	0	0	0	0	0	0	0	0
13H2/48-51 MM	0	0	0	0	0	0	0	0	0	0
13H2/85-88 MM	0	0	0	0	0	0	0	0	0	0
13H2/125-128 MM	0	0	0	0	0	0	0	0	0	0
13H3/10-13 MM	0	0	0	0	0	0	0	0	0	0
13H3/47-50 MM	2	2	0	0	0	2	0	0	0	0
13H3/59-62 S	0	0	0	0	0	0	0	0	0	0
13h3/90-93 MM	0	0	0	0	0	0	0	0	0	0
13h3/134-137 MM	0	0	0	0	0	0	0	0	0	0
13H4/10-13 MM	0	0	0	0	0	0	0	0	0	0
13H4/49-52 MM	0	0	0	0	0	0	0	0	0	0
13H4/85-88 MM	0	0	0	0	0	0	0	0	0	0
13H4/120-123 MM	0	0	0	0	0	0	0	0	0	0
13H5/9-12 MM	0	0	0	0	0	0	0	0	0	0
13h5/49-52 MM	0	0	0	0	0	0	0	0	0	0
13H5/93-96 MM	0	0	0	0	0	0	0	0	0	0
13H5/140-143 MM	0	0	0	0	0	0	0	0	0	0

INDEX:
V= Varves
M= Massive
IL=Indistinct laminae
MM=Massive muds
FS=Fine sand
S=Sand

Foraminiferal data of Hole 1034B

Fissurina spp.	T. nana	T. charlottensis	Planktics	N. stella	B. pacifica	S. stalkeri	Others
0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0
0	0	0	0	2	0	0	0
0	0	0	0	0	0	2	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	2	0	0	0	Angulogenna fluens (1)
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	1	1	Arcellacean (2)
0	0	0	0	0	1	0	0
1	0	0	3	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	M. fusca (1)
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	1	0	2	0	0
1	0	0	0	0	0	0	0
0	0	0	3	0	0	0	0
0	0	0	4	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	4	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	3	0	0	0	I. helenae (1)
0	0	0	5	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	0	0	0
0	0	0	1	1	0	0	0
0	0	0	2	1	0	0	0
0	0	0	2	0	0	0	0
0	0	0	4	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	5	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	4	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	Chilostomella oolina (2)
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	32	0	64	44	0	I.norcrossi(72);C.reniformae(12);N.labradorica(4)
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	I.norcrossi(4);S.tenuis(28);C.reniformae(4);M.fusca(22)
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	I.norcrossi(16);S.tenuis(14);C.reniformae(4);M.fusca(14)
0	0	0	0	0	0	0	I.norcrossi(12);S.tenuis(14);C.reniformae(9);M.fusca(12)
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	I. norcrossi (2)
0	0	0	0	0	0	0	S. tenuis (6)
0	0	0	0	4	0	0	I. norcrossi(12)
0	0	0	0	0	0	0	I.norcrossi(45);I.helenae(54);C.reniformae(15);S.tenuis(18)
0	0	0	0	6	0	0	I.norcrossi(22);I.helenae(34);C.reniformae(14);S.tenuis(14)
0	0	0	0	0	0	0	I. norcrossi (26); I.helenae (24); C. reniformae (6)
0	0	0	0	0	0	0	I.norcrossi(68);I.helenae(48);C.reniformae(16);S.tenuis(16)
0	0	0	0	0	0	0	I.norcrossi(54);I.helenae(36);S.tenuis(16);N.labradorica(4)
0	0	0	0	0	0	0	I.norcrossi(15);Ihelenae(15);S.tenuis(18);N.labradorica(6)
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	I.helenae (24)
0	0	0	0	0	0	0	I.norcrossi(32)
0	0	0	0	0	0	0	I.helenae (16)
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

0	0	0	0	0	0	0			0
0	0	0	0	0	0	0			0
0	0	0	0	0	0	0			0
0	0	0	0	0	0	0			0
0	0	0	0	0	0	0			0
0	0	0	0	0	0	0			0
0	0	0	0	0	0	0			0
0	0	0	0	0	0	0			0
0	0	0	0	0	0	0			0
0	0	0	0	0	0	0			0
0	0	0	0	0	0	0			0
0	0	0	0	0	0	0			0
0	0	0	0	0	0	0			0
0	0	0	0	0	0	0			0
0	0	0	0	0	0	0			0
0	0	0	0	0	0	0			0
0	0	0	0	0	0	0			0

Appendix 4. Fractional abundance and standard error associated with each species counted in selected samples

Sample	34/8H1/140-143	34/9H1/46-49	34/9H2/15-18	34/9H2/45-48	34/9H3/62-65	34/9H3/97-100	34/9H3/102-105	34/9H3/108-110	34/9H3/125-128	34/9H4/28-32	34/9H4/38-41
Total Count	604	64	58	60	249	94	56	188	132	63	80
Diversity	9	5	5	6	7	6	3	7	5	5	3
C. exacavatum	0	0.0938	0.1724	0.1500	0.1928	0.0426	0.0000	0.0851	0.1667	0.1429	0.5000
standard error ±	0	0.0714	0.0972	0.0904	0.0490	0.0408	0.0000	0.0399	0.0636	0.0864	0.1096
C. halladense	0	0	0	0	0.0723	0.0000	0.0000	0.0426	0.0000	0.0000	0.0000
standard error ±	0	0	0	0	0.0322	0.0000	0.0000	0.0289	0.0000	0.0000	0.0000
C. foraminosum	0	0	0	0	0.2048	0.0000	0.0000	0.0638	0.0000	0.0000	0.0000
standard error ±	0	0	0	0	0.0501	0.0000	0.0000	0.0349	0.0000	0.0000	0.0000
B. frigida	0.1192	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
standard error ±	0.0258	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
L. fletcheri	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
standard error ±	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
S. feylingi	0.2583	0.0000	0.0000	0.1000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
standard error ±	0.0349	0.0000	0.0000	0.0759	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2000
B. eligantissima	0.2450	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0877
standard error ±	0.0343	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Fissurina spp.	0	0	0	0	0	0	0	0	0	0	0
standard error ±	0	0	0	0	0	0	0	0	0	0	0
Trochamnina spp.	0.0530	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
standard error ±	0.0179	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N. stella	0.1060	0.0000	0.0000	0.0000	0.0000	0.0638	0.0000	0.0000	0.0000	0.0000	0.0000
standard error ±	0.0245	0.0000	0.0000	0.0000	0.0000	0.0494	0.0000	0.0000	0.0000	0.0000	0.0000
B. pacifica	0.0728	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
standard error ±	0.0207	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
S. agglutinata	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
standard error ±	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
M. fusca	0.0000	0.3438	0.2414	0.2000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
standard error ±	0.0000	0.1164	0.1101	0.1012	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
I. helenae	0.0000	0.0000	0.0000	0.0000	0.2169	0.3617	0.4286	0.2553	0.2879	0.2381	0.3000
standard error ±	0.0000	0.0000	0.0000	0.0000	0.0512	0.0971	0.1296	0.0623	0.0772	0.1052	0.1004
I. norcrossi	0.1192	0.0625	0.2759	0.2000	0.1807	0.2340	0.4643	0.3617	0.4091	0.2381	0.0000
standard error ±	0.0258	0.0593	0.1150	0.1012	0.0478	0.0856	0.1306	0.0687	0.0839	0.1052	0.0000
C. reniformae	0.0199	0.0625	0.0690	0.1500	0.0602	0.1489	0.1071	0.0851	0.0000	0.0000	0.0000
standard error ±	0.0111	0.0593	0.0652	0.0904	0.0296	0.0720	0.0810	0.0399	0.0000	0.0000	0.0000
N. labradorica	0.0066	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0303	0.0952	0.0000
standard error ±	0.0065	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0292	0.0725	0.0000
S. tenuis	0.0000	0.4375	0.2414	0.2333	0.0723	0.1489	0.0000	0.0851	0.1212	0.2857	0.0000
standard error ±	0.0000	0.1215	0.1101	0.1070	0.0322	0.0720	0.0000	0.0399	0.0557	0.1116	0.0000
C. microgranulosum	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
standard error ±	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Buliminella sp.	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
standard error ±	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N. digitata	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
standard error ±	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Rosalina spp.	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
standard error ±	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Planktics	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
standard error ±	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Appendix 4. Fractional abundance and standard error associated with each species counted in selected samples

34/9H4/48-51 50 2	33/2H5/139-140 186 10	33/2H5/146-149 56 7	33/2H6/60-63 63 10	33/3H3/67-70 50 12	33/3H5/124-126 66 12	33/3H7/76-79 50 9	33/4H1/42-45 51 7	33/4H1/140-142 69 4	33/4H2/51-54 60 8	33/4H7/77-79 63 8	33/5H1/60-63 52 4
0.3600	0.1290	0.2143	0.1746	0.1600	0.1515	0.1600	0.1569	0.0290	0.1667	0.1270	0.0000
0.1330	0.0482	0.1075	0.0937	0.1065	0.0865	0.1016	0.0998	0.0396	0.0943	0.0822	0.0000
0.0000	0.0161	0.0536	0.0159	0.0400	0.0455	0.1000	0.0196	0.0000	0.0167	0.0317	0.0000
0.0000	0.0181	0.0590	0.0309	0.0543	0.0503	0.0832	0.0381	0.0000	0.0324	0.0433	0.0000
0.0000	0.0000	0.0000	0.0317	0.0200	0.0303	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0433	0.0388	0.0414	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0645	0.2857	0.3016	0.2200	0.2727	0.2400	0.2549	0.5217	0.1833	0.2540	0.1538
0.0000	0.0353	0.1183	0.1133	0.1148	0.1074	0.1184	0.1196	0.1179	0.0979	0.1075	0.0981
0.0000	0.1613	0.1964	0.1587	0.0600	0.2273	0.1600	0.2745	0.4203	0.2667	0.2381	0.3846
0.0000	0.0529	0.1041	0.0902	0.0658	0.1011	0.1016	0.1225	0.1165	0.1119	0.1052	0.1322
0.0000	0.4516	0.0714	0.1746	0.0400	0.0455	0.1800	0.0000	0.0000	0.0167	0.1905	0.0769
0.0000	0.0715	0.0675	0.0937	0.0543	0.0503	0.1065	0.0000	0.0000	0.0324	0.0970	0.0724
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0	0.0484	0.0536	0	0.0200	0.0303	0.0200	0	0	0	0.0794	0
0	0.0308	0.0590	0	0.0388	0.0414	0.0388	0	0	0	0.0667	0
0.0000	0.0806	0.1250	0.0794	0.0000	0.0758	0.0600	0.0980	0.0000	0.0167	0.0000	0.0000
0.0000	0.0391	0.0866	0.0667	0.0000	0.0638	0.0658	0.0816	0.0000	0.0324	0.0000	0.0000
0.0000	0.0000	0.0000	0.0159	0.0200	0.0152	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0309	0.0388	0.0295	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0161	0.0000	0.0159	0.0200	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0181	0.0000	0.0309	0.0388	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0200	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0388	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0152	0.0200	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0295	0.0388	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0161	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0181	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.6400	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.1330	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0455	0.0000	0.0196	0.0000	0.0167	0.0317	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0503	0.0000	0.0381	0.0000	0.0324	0.0433	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0200	0.0152	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0388	0.0295	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0161	0.0000	0.0317	0.3400	0.0000	0.0200	0.1373	0.0290	0.3167	0.1270	0.1538
0.0000	0.0181	0.0000	0.0433	0.1313	0.0000	0.0388	0.0944	0.0396	0.1177	0.0822	0.0981

Appendix 4. Fractional abundance and standard error associated with each species counted in selected samples

33/5H1/70-74	33/5H4/94-97	33/5H4/106-109	33/5H4/115-118	33/5H5/2-5	33/5H5/8-11	33/5H5/14-17	33/5H5/58-62	33/5H5/64-68	33/5H5/68-72	33/5H5/74-78	33/5H5/113-116	33/5H7/52-55
108	52	51	63	560	1088	736	50	132	102	114	104	104
5	8	4	9	10	12	7	5	3	6	5	4	4
0.0278	0.0385	0.0000	0.0952	0.2411	0.1912	0.2391	0.2200	0.0455	0.1961	0.0000	0.0000	0.0769
0.0310	0.0523	0.0000	0.0725	0.0354	0.0234	0.0308	0.1148	0.0355	0.0771	0.0000	0.0000	0.0512
0.0000	0.0000	0.0000	0.0476	0.0357	0.0368	0.0000	0.0400	0.0000	0.0196	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0526	0.0154	0.0112	0.0000	0.0543	0.0000	0.0269	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0089	0.0074	0.0000	0.0000	0.0000	0.0196	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0078	0.0051	0.0000	0.0000	0.0000	0.0269	0.0000	0.0000	0.0000
0.0278	0.1923	0.1373	0.4921	0.3571	0.3603	0.2174	0.2400	0.1818	0.0588	0.2632	0.2308	0.2308
0.0310	0.1071	0.0944	0.1235	0.0397	0.0285	0.0298	0.1184	0.0658	0.0457	0.0808	0.0810	0.0810
0.0556	0.1346	0.1176	0.1905	0.2411	0.1912	0.3043	0.0000	0.0000	0.0000	0.1053	0.0000	0.0000
0.0432	0.0928	0.0884	0.0970	0.0354	0.0234	0.0332	0.0000	0.0000	0.0000	0.0563	0.0000	0.0000
0.7870	0.5000	0.6667	0.0635	0.0625	0.1324	0.0870	0.3600	0.7727	0.4706	0.4211	0.3077	0.1538
0.0772	0.1359	0.1294	0.0602	0.0200	0.0201	0.0204	0.1330	0.0715	0.0969	0.0906	0.0887	0.0693
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0278	0	0	0.0476	0	0.0074	0	0	0	0	0	0	0
0.0310	0	0	0.0526	0	0.0051	0	0	0	0	0	0	0
0.0000	0.1346	0.0000	0.0000	0.0000	0.0074	0.0000	0.0000	0.0000	0.0000	0.0526	0.0000	0.0000
0.0000	0.0928	0.0000	0.0000	0.0000	0.0051	0.0000	0.0000	0.0000	0.0000	0.0410	0.0000	0.0000
0.0000	0.0000	0.0000	0.0159	0.0089	0.0147	0.0217	0.0000	0.0000	0.0000	0.0000	0.3077	0.0000
0.0000	0.0000	0.0000	0.0309	0.0078	0.0072	0.0105	0.0000	0.0000	0.0000	0.0000	0.0887	0.0000
0.0000	0.0769	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0724	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0089	0.0074	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0078	0.0051	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0192	0.0784	0.0159	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0373	0.0738	0.0309	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0317	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0433	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0089	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0078	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0192	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0373	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0089	0.0294	0.0217	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0078	0.0100	0.0105	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0147	0.0652	0.1200	0.0000	0.1765	0.1579	0.1538	0.5385
0.0000	0.0000	0.0000	0.0000	0.0000	0.0072	0.0178	0.0901	0.0000	0.0740	0.0669	0.0693	0.0958

Appendix 4. Fractional abundance and standard error associated with each species counted in selected samples

33/5H7/57-60	33/5H7/67-70	33/6H1/57-60	33/6H2/145-148	33/6H5/7-10	33/6H5/16-19	33/6H5/24-27	33/6H5/57-61	33/6H5/70-73	33/6H5/126-120	33/6H6/29-32	33/6H6/127-130	33/7H1/29-32
120	64	152	184	120	69	176	180	528	88	104	224	1760
5	3	6	7	6	8	6	3	9	2	3	2	8
0.0000	0.0000	0.2632	0.1087	0.1333	0.0870	0.1818	0.0333	0.1667	0.1818	0.0000	0.0000	0.6682
0.0000	0.0000	0.0700	0.0450	0.0608	0.0665	0.0570	0.0262	0.0318	0.0806	0.0000	0.0000	0.0220
0.0000	0.0000	0.0395	0.0000	0.0000	0.0435	0.0455	0.0000	0.0303	0.0000	0.0000	0.0000	0.0364
0.0000	0.0000	0.0310	0.0000	0.0000	0.0481	0.0308	0.0000	0.0140	0.0000	0.0000	0.0000	0.0087
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0152	0.0000	0.0000	0.0000	0.0227
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0104	0.0000	0.0000	0.0000	0.0070
0.2667	0.1250	0.2105	0.5000	0.2000	0.1304	0.0000	0.0000	0.0227	0.0000	0.2308	0.0714	0.0727
0.0791	0.0810	0.0648	0.0722	0.0716	0.0795	0.0000	0.0000	0.0127	0.0000	0.0810	0.0337	0.0121
0.0000	0.0000	0.0000	0.2609	0.0000	0.1304	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0045
0.0000	0.0000	0.0000	0.0834	0.0000	0.0795	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0031
0.4667	0.6250	0.3684	0.0652	0.3333	0.3913	0.2273	0.4333	0.0000	0.0000	0.6923	0.9286	0.1636
0.0893	0.1186	0.0767	0.0357	0.0843	0.1152	0.0619	0.0724	0.0000	0.0000	0.0887	0.0337	0.0173
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0667	0	0	0.0217	0	0.0435	0	0	0.0076	0	0	0	0
0.0446	0	0	0.0211	0	0.0481	0	0	0.0074	0	0	0	0
0.0000	0.0000	0.0000	0.0217	0.0667	0.0000	0.0455	0.0000	0.0000	0.0000	0.0000	0.0000	0.0045
0.0000	0.0000	0.0000	0.0211	0.0446	0.0000	0.0308	0.0000	0.0000	0.0000	0.0000	0.0000	0.0031
0.0667	0.0000	0.0526	0.0000	0.2000	0.0000	0.4545	0.5333	0.5682	0.8182	0.0769	0.0000	0.0000
0.0446	0.0000	0.0355	0.0000	0.0716	0.0000	0.0736	0.0729	0.0423	0.0806	0.0512	0.0000	0.0000
0.0000	0.0000	0.0526	0.0000	0.0000	0.0000	0.0000	0.0000	0.0682	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0355	0.0000	0.0000	0.0000	0.0000	0.0000	0.0215	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0667	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0446	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0455	0.0000	0.0076	0.0000	0.0000	0.0000	0.0273
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0308	0.0000	0.0074	0.0000	0.0000	0.0000	0.0076
0.0000	0.0000	0.0000	0.0217	0.0000	0.1304	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0211	0.0000	0.0795	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1136	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0271	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.1333	0.2500	0.0000	0.0000	0.0000	0.0435	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0608	0.1061	0.0000	0.0000	0.0000	0.0481	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Appendix 4. Fractional abundance and standard error associated with each species counted in selected samples

33/7H2/8-11	33/7H2/59-62	33/7H2/110-113	33/7H5/29-31	33/8H1/127-130	33/8H2/29-32	33/12H2/25-28	33/12H2/79-82	33/12H2/128-131
219	262	134	237	57	137	100	290	90
3	9	9	8	6	6	4	8	5
0.0137	0.5344	0.1940	0.1646	0.0702	0.1971	0.5600	0.4138	0.3333
0.0154	0.0604	0.0670	0.0472	0.0663	0.0666	0.0973	0.0567	0.0974
0.0000	0.0611	0.0299	0.0506	0.0175	0.0584	0.0000	0.2241	0.3000
0.0000	0.0290	0.0288	0.0279	0.0341	0.0393	0.0000	0.0460	0.0947
0.0000	0.0153	0.0000	0.0127	0.0175	0.0000	0.1200	0.0345	0.1333
0.0000	0.0148	0.0000	0.0142	0.0341	0.0000	0.0637	0.0210	0.0702
0.0000	0.0153	0.0746	0.0506	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0148	0.0445	0.0279	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0299	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0288	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.9726	0.0076	0.1194	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0218	0.0105	0.0549	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0.0000	0.0000	0.0000	0.1392	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0441	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0299	0.0000	0.0000	0.0219	0.0000	0.0000	0.0000
0.0000	0.0000	0.0288	0.0000	0.0000	0.0245	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0127	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0142	0.0000	0.0000	0.0000	0.0000	0.0000
0.0137	0.0038	0.0896	0.0000	0.6842	0.5474	0.2000	0.2069	0.1333
0.0154	0.0075	0.0483	0.0000	0.1207	0.0833	0.0784	0.0466	0.0702
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.2214	0.2687	0.0000	0.0000	0.0000	0.0400	0.1034	0.1000
0.0000	0.0503	0.0751	0.0000	0.0000	0.0000	0.0384	0.0351	0.0620
0.0000	0.0000	0.1642	0.1519	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0627	0.0457	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0172	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0150	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0763	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0322	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0076	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0105	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.1579	0.0584	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0947	0.0393	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0833	0.0526	0.1022	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0310	0.0580	0.0507	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

CONCLUSIONS

The application of micropaleontology to address a wide variety of environmental problems is a relatively new field of science called "Environmental Micropaleontology". This dissertation is based on the study of testate rhizopods as proxies for both anthropogenic and natural change in environmental conditions. The dissertation is divided into two parts. The first part demonstrates use of the arcellaceans (thecamoebians) as proxies for lake bottom acidity, chemical pollution, remediation and long term environmental stress in James Lake. The chemical pollution in this lake was caused by dumping of waste rock from a nearby pyrite mine on its shore. The second part demonstrates use of the benthic foraminifera as proxies for paleoceanographic and paleoclimatic changes in a coastal inlet on southern Vancouver Island, British Columbia. Benthic foraminiferal and sedimentological analysis of the core sediments from the inlet have provided information on the periodicity and magnitude of Holocene seismic activity in southern British Columbia.

Arcellaceans (Thecamoebians) are testate rhizopods with agglutinated shells, which occur in freshwater and brackish environments. They have simple morphology, and their asexual reproductive mode results in the production of environmentally influenced "strains" that are useful in identifying chemically polluted and remediated benthic environments in the lakes.

The southwestern portion of James Lake in northeastern Ontario has been impacted by dumping of waste rock from a pyrite mine. High levels of Fe, Al and SO_4, and low pH (2.0-5.5) were recorded in the lake. Lake configuration and current direction

from north to south result in the contaminated area being restricted to the southwestern part of the lake, and almost neutral pH and low metal levels were recorded elsewhere. Arcellacean faunas indicate that *Arcella vulgaris* is able to thrive in highly acidic environments (pH range between 2.0 - 5.5). The absence of arcellaceans indicative of contaminated substrates in higher pH lakes, such as Centropyxids and *Difflugia protaeiformis* strains, suggests that pH is the dominant control on the distribution of this assemblage. Arcellacean analysis from a core at the contaminated site indicates that natural acidification (pH values <5.5) in southwestern part of James Lake have existed for at least 1300 years, predating mining activity. Prior to that time high proportions of centropyxid species indicate less acid conditions (pH> 5.5) prevailed for several thousand years. Six assemblages representative of distinct arcellacean habitats were recognized in sediment-water interface samples collected in the lake using Q-mode cluster analysis. They are (1) *Arcella* Assemblage; (2) Higher Diversity *Arcella* Assemblage; (3) *Difflugia* Assemblage; (4) *Difflugia protaeiformis* Assemblage; (5) *Lesquereusia* Assemblage; and (6) *Centropyxis* assemblage. R-mode cluster analysis of these distributional data indicates that arcellacean strains from within the same species are useful for discriminating environments. The seasonally planktic and thus readily transported *Cucurbitella tricuspis* dominates most samples and thus should not be used for intralake studies. *Arcella vulgaris* overwhelmingly dominates low pH environments (<5.5) near the mine site where Shannon Diversity Index values of <1.000 were recorded. The results further indicate that while *Difflugia protaeiformis* "claviformis" is an ideal indicator of industrial contamination under higher pH conditions, the *D. protaeiformis* "amphoralis" and

"acuminata" strains are more closely linked to uncontaminated muddy substrates characterized by high proportions of diatoms, a probable important food source. Presence of *Lesquereusia spiralis* seems to be partially linked to substrate with greater numbers typically found in coarser substrates.

Two long records from ODP Holes 1033B (105 m thick) and 1034B (118 m thick) collected during Leg 169S from Saanich Inlet were analyzed for benthic foraminifera. Sediments of this anoxic fjörd on the southern part of Vancouver Island consist of varved clays interbedded with slightly coarser massive layers. The fauna is impoverished and only 25 species of benthic foraminifera were identified which were predominantly shallow water, benthic, calcareous forms. Most of the samples contained few (average of 25-30) specimens, but massive layers contained statistically (sign test) higher numbers and diversity of benthic foraminifera than varves. A high proportion (>50%) of the fauna was found to be broken/damaged. The presence of arcellaceans and a high proportion of broken/damaged foraminifera found in massive layers supports the hypothesis that they were transported from both the coastal regions and shallow well oxygenated parts of the inlet and deposited on the anoxic bottom of Saanich Inlet during seismically induced subaqueous debris flows. Intact benthic foraminifera within the varves are autochthonous, capable of withstanding dysoxic/anoxic conditions, and broken specimens are usually of allochthonous origin being transported to the deeper anoxic parts of the inlet during spring freshet along with mineral rich silt. Based on the frequency of massive layers in these cores, an estimated periodicity of earthquakes (minimum M >4 -5)average to be every

170 years at narrower and steeper site 1033, and larger earthquakes are estimated to occur every 280 years at wider and less steep site1034.

Q-mode cluster analysis of the foraminiferal data was used to define the five distinct biofacies. They are; *Stainforthia feyling-Buccella frigida* biofacies, *Buccella frigida-Lobatula fletcheri* biofacies, *Nonionella stella-Stainforthia feylingi* biofacies, *Islandiella helenae-Spirosigmoilina tenuis* biofacies, and *Siphonaperta stalkeri-Cribroelphidium excavatum* biofacies. The distribution of these biofacies is controlled primarily by the process of Late Pleistocene deglaciation and associated sea-level changes and development of anoxic conditions during early Holocene in the Saanich Inlet.