Grain-size analysis and Arcellinida as tools for inferring
paleoclimatological variability: a case study from Holocene
Canadian Subarctic lake sediments.

By

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Abstract

The central Northwest Territories of the Canadian Subarctic, and the myriad of lakes found therein, has through previous research been shown to archive records of past Holocene climate variability. Due to the low temporal resolution of previous paleoclimatic reconstructions questions remain as to past rates of natural climate change, a deficiency of concern to policy makers and modelers responsible with addressing human induced climate change. Two paleolimnological proxies of climate variability, end-member mixing analysis (EMMA) of lake grain-size distributions and the Arcellinida were further developed to increase the temporal resolution of paleoclimate reconstructions and provide a more complete picture of environmental response to past climate variability. A mm-interval subsampling strategy made possible through use of a custom-designed sledge microtome combined with EMMA of lake sediment cores significantly increased the temporal resolution of paleoclimate reconstructions. EMMA of lake sediment cores was used to describe changes in lake catchment hydrology and track the rate of climate deterioration and subsequent amelioration associated with known Holocene events such as the Holocene Climate Optimum (HCO) and the onset of the Neoglacial. Arcellinida as demonstrated here, are sensitive to treeline dynamics. Due to their well-preserved dissolution-resistant tests, rapid generation time and trophic position within lacustrine environments they offer unique insight into climate variability and change. Arcellinida are also characterized by ecophenotypes, which respond markedly to changing environmental conditions making them valuable tools for reconstructing environmental change. Three ecological transitions were seen in the observed Arcellinida communities through the past *ca.* 6600 cal yBP. Zone 1 spanned *ca.* 6600-2800 cal yBP

and characterized the hydroecology of the lake during the HCO. Zone 2 spanned *ca.* 2800-140 cal yBP, which represents the Neoglacial. Zone 3 spans *ca.* 140 cal yBP to present and archives the recovery of the region from the Little Ice Age. Further development of these proxies will help to constrain the rate of climate variability and increase our understanding of the many ways in which the environment responds to climate change. This has implications not only for the Canadian Subarctic but for the Taiga biome, the largest terrestrial biome in the world.

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1 Chapter: Introduction

The central Northwest Territories within the Canadian Subarctic, and the abundant lakes therein, has previously been shown to be an area sensitive to past climate variability (MacDonald et al. 1993). Due to the low temporal resolution of previous paleoclimatic reconstructions carried out in the region there remains uncertainty regarding the rate of climate variability possibly within the area, a concern to policy makers and modelers mandated to predict future climate states. Two paleolimnological proxies of climate variability, end-member mixing analysis (EMMA) of lake grain-size distributions (GSDs) and the shelled protists, Arcellinida (testate lobose amoeba, Arcellacea), were further developed to increase the temporal resolution of paleoclimate reconstructions and to provide a more complete picture of the environmental response to past climate variability.

The sensitivity of the northern treeline to climate variability makes it an ideal location for paleoecological studies of past climate changes (Pienitz et al. 1999; Huang et al. 2004). Lakes are abundant in the central NT and their sediments contain continuous archives of biological, chemical, and physical proxies of recent and past environmental conditions that can be linked to climate (Chen et al. 2004; Conroy et al. 2008; MacDonald et al. 2009). Climate variability tends to be greater and occurs more rapidly in polar regions (ACIA 2005). The Arctic biome is very sensitive to climate variability as most of the flora and fauna found there are living at or near their ecological thresholds. Paleoecological proxy data archived in natural systems (e.g. lakes and peatlands) provide continuous records of climate variability that at southern latitudes might be too subtle to

detect. Previous paleoclimate reconstructions have identified three main stages of landscape development. The first stage occurred between ~8500 cal yBP and 6300 cal yBP when birch dominated shrub tundra transitioned to spruce forest tundra following regional deglaciation (Huang et al. 2004). At ca. 8200 BP a hemispheric cooling event occurred, triggered by the rapid northward drainage of the super lake formed by the glacial Lakes Agassiz and Ojibway (Clarke et al. 2004). This cold event has been identified in both the GRIP and GISP ice cores from Greenland, and it seems to have been the most significant climate excursion of the past 10,000 years (Clarke et al. 2004). During this roughly 200-year interval mean temperature is thought to have dropped by as much as 3-5°C (Clarke et al. 2004). The second stage was marked by a rapid forest expansion to about 50 km north of the present day treeline, likely reflecting a northward movement of the polar front between ~6300 and 3000 cal yBP (Moser & MacDonald 1990; MacDonald et al. 1993; Huang et al. 2004). The final stage began with the onset of the Holocene Neoglacial when cooling at 3000 cal yBP resulted in southward retreat of the treeline to its current position (Huang et al. 2004). This previous work has been successful in recognizing broad-scale patterns of Holocene natural climate variability, but there still remains uncertainty as to the rate of climate variability due to the low temporal resolution of these previous studies.

This study of paleoclimatic and paleoenvironmental data from northern treeline lakes was carried out to increase the temporal resolution of Holocene climate variability and provide additional insight into the environmental response of the region to past climate events. This was accomplished through high-frequency paleoclimate reconstructions of

frozen sediment cores through the use of a novel core microtome described in Chapter 2. This was paired with the development of two novel paleolimnological proxies of climate variability, end-member mixing analysis (EMMA) of lake GSDs (Chapter 3) and Arcellinida (Chapter 4 & 5) were used to characterize the rate and magnitude of past climate variability. The development of new proxies is important as single proxies can sporadically become decoupled from climate forcing. Paleoclimate histories utilizing multiple proxies are thus more robust and coherent since they guard against the complex interactions among parameters within natural systems.

Most lacustrine environments in the north (Gasirowski 2008) are characterized by low sedimentation rates, where the standard core subsampling resolution of 0.5-10 cm is typically insufficient to detect many important paleoclimate and paleoenvironmental signals (Patterson 1993). This is especially true in subarctic lakes where low sedimentation rates (0.01-0.04 cm/yr) (Crann et al. 2015; Appendix A.7) meant that only a mm-interval sampling strategy would be sufficient to improve our understanding of rates of environmental change at the subdecadal to decadal scales critical to recognizing periodic signatures of natural processes at resolutions high enough to provide practical guidance for policy makers and planners. This was the impetus for the development of the freeze core sledge microtome presented in Chapter 2. The microtome allows for the mm-scale subsampling strategy required to examine sediment cores at decadal to sub-decadal resolution. High resolution core analysis using paleoclimate proxies allows for the investigation of decadal to multi-decadal climate modes of variability that have modulated the region throughout the Holocene.

Clastic materials deposited in lakes potentially provide an important source of information about changes in regional hydrology and global atmospheric circulation (Xiao et al. 2012; Francus et al. 2002; Sun et al. 2002; Chen et al. 2004; Cockburn & Lamoureux 2008a; Conroy et al. 2008; Kirby et al. 2010). The GSD of a sample of lake sediment can provide insight into exogenic processes responsible for the deposition of sediment onto the lake bottom (IJmker et al. 2012), because a relationship exists between clastic and hydraulic interactions within a lake and its catchment (Chen et al. 2004; Sun et al. 2002; Conroy et al. 2008; Kirby et al. 2010; Francus et al. 2002). The results of previous studies have demonstrated that lake GSDs are correlated with snowmelt intensity, an index reflecting the hydraulic energy available for sediment transport (Francus et al. 2008; Francus et al. 2002; Cockburn & Lamoureux 2008a; Cockburn & Lamoureux 2008b). Thus GSDs of lake sediments represent a potential new proxy for constraining historical climate variability. Issues arise in identifying specific grain-size components that are associated with climate related catchment erosional processes (Cockburn and Lamoureux 2008b). End-member mixing analysis (EMMA) is a new and promising methodology that aims to provide a genetic interpretation of GSDs with minimal assumptions (Weltje & Prins 2003; Weltje & Prins 2007; Dietze et al. 2012). Each EM is thought to represent depositional processes that can be linked to lake-catchment hydraulic energy and thus reflect a climate dependent process. Chapter 3 outlines the development of this tool as a proxy for Holocene climate variability in the Canadian Subarctic. EMMA does not suffer from the need for large subsamples, meaning it is well suited to a mm-subsampling strategy of frozen lake sediment cores. The results

presented here show that primary factors controlling hydraulic energy include: density of catchment vegetation, ratio of winter to summer precipitation and sediment availability. This has permitted the and recognition of climate deterioration during the 8200 cal yBP cooling event, climate amelioration during the Holocene Climate Optimum (5500-3000 cal yBP) and the onset of the Neoglacial cooling at 2600 cal yBP.

Arcellinida are characterized by lobose pseudopods and the construction of a generally agglutinated unilocular test. The great preservation potential of their tests, rapid reproductive turnover rates and high concentrations in lake sediments (500-3000 specimens per ml in temperate lakes; Patterson and Kumar 2002) make them a valuable environmental proxy. Although few studies have used Arcellinida to track Holocene climate dynamics (McCarthy et al. 1995; Asioli et al. 1996), with only one completed in the Canadian Arctic (Dallimore et al. 2000), this previous work has demonstrated the potential of this taxa as a proxy of Holocene climate dynamics. Previous studies have linked the size of Arcellinida tests to the duration of the reproductive season (Collins et al. 1990; Dallimore et al. 2000; Asioli et al. 1996; Lorencová 2009), with smaller than average test sizes being associated with longer reproductive seasons and warmer conditions. McCarthy et al. (1995) successfully tracked regional Holocene climate dynamics in Atlantic Canada using a study of Arcellinida assemblages from three lakes. They identified community shifts that occurred in response to deglaciation, the Holocene Climate Optimum (HCO) and the onset of the Neoglacial. In their study on Richards Island, NT, Dallimore, Schröder-Adams, and Dallimore (2000) found that Arcellinida were only able to colonize the lake after *ca.* 3000 cal yBP. They identified horizons

associated with environmental improvement at *ca.* 1700 and 300 cal yBP where population abundances increased. No studies have documented Arcellinida community changes in the Canadian Subarctic. In addition, all previous studies have been at a coarse temporal resolution that makes it difficult to constrain the rate of Holocene climate variability. This study seeks to develop and refine Arcellinida as proxies of Holocene climate dynamics in the central NT region of the Canadian Subarctic.

A key feature of Arcellinida test morphology is their ecophenotypic response to changing conditions within their environment. This greatly enhances the utility of the group to characterize both modern and paleoenvironments. Arcellinida also display a wide variety of phenotypic variability, which may not be directly related to autoecological pressures. A pragmatic statistical approach was developed to evaluate the validity of ecophenotypes in Arcellinida as outlined in Chapter 4. The outcome of this research will aid in the discrimination of test morphologies that signify different environmental conditions.

Chapter 5 outlines the results of a follow-up study of a core from Carleton Lake, previously analyzed by Upiter et al. (2014), where a large shift in the chironomid community was observed to have occurred *ca.* 4600-4000 cal yBP. During this interval taxa more closely associated with tundra lakes were replaced by taxa more common in boreal environments. Comparison of the Upiter et al. (2014) results to a previous study indicated that the timing of forestation at Carleton Lake lagged behind that observed at nearby Queen's Lake by 1000 years (MacDonald et al. 1993). The discrepancy in timing was hypothesized to be due to chironomid assemblages being driven by ecological factors

in addition to air temperatures. Analysis of the Arcellinida communities within the Carleton Lake core was carried out to better constrain the timing and rate of treeline movement around Carleton Lake. The work was also carried out to better assess the utility of Arcellinida as paleoclimate indicators in the north. The results presented here show that the Carleton catchment became forested *ca.* 5500 cal yBP, in line with previous studies from other sites. The usage of Arcellinida strains as informal infrasubspecific taxonomic units permitted the tracking of the Neoglacial onset. Cooler temperatures led to prolonged test growth prior to reproduction in *Diffugia globulosa* and *Diffugia glans*, leading to larger tests in these two species during cold phases. The results also demonstrate that there was a significant shift in the Arcellinida assemblage at *ca.* 140 cal yBP, supporting results of previous studies of diatom paleoecology carried out in the region (Rühland & Smol 2005), that discriminated the onset of late 19th century warming at the conclusion of the Little Ice Age.

The development of novel proxies will help to constrain the rate of climate variability, produce robust paleoclimate reconstructions and increase our understanding of the many ways in which the environment in the central Northwest Territories responds to change. This has implications not only for the Canadian Subarctic but for the Taiga biome, the largest terrestrial biome in the world.

2 Chapter: A sledge microtome for high resolution subsampling of freeze cores

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2.2 Foreword

This chapter was the first peer-reviewed publication to come out of the NSERC strategic grant “Impact of Climate Change on the Long-Term Viability of the Strategically Important Tibbitt to Contwoyto Winter Road, Northwest Territories”. This turned out to be fitting, as the sledge microtome has been integral to the overall success of the project. The development and building of this instrument addressed the need for a high resolution freeze core sub-sampling methodology to meet the mandate of the research. The low sedimentation rates of our lakes (0.01-0.04 cm/yr) (Crann et al. 2015; Appendix A.7) meant that only a mm-interval sampling strategy would be sufficient to improve our understanding of rates of environmental change at the subdecadal to decadal scales critical to recognizing periodic signatures of natural processes at resolutions high enough to provide practical guidance for policy makers and planners.

Little has been changed from the published document. It has been formatted to fit within the Carleton University Thesis Template. Illustrations can be found in Appendix B. Tim Patterson is responsible for the original concept and design. I was responsible for troubleshooting the device for use with freeze cores and communicating with the engineering team. I was responsible for writing and drafting figures for the manuscript. All co-authors added feedback and helped with revision of the manuscript. It should be cited as follows:

Macumber, A.L. et al., 2011. A sledge microtome for high resolution subsampling of freeze cores. *J Paleolimnol* 45:307-310. DOI: 10.1007/s10933-010-9487-4

2.3 Abstract

We describe a sledge microtome designed for the high-resolution subsampling of freeze cores. This inexpensive freeze-core microtome is capable of producing precise subsamples at mm to sub-mm resolution without sediment loss and cross-contamination. Such a subsampling resolution permits recognition of sub-decadal to annual events even in systems with low sedimentation rates. The freeze-core microtome is particularly useful for obtaining high-resolution subsamples at the environmentally important sediment water interface due to freeze corers being capable of capturing this boundary with minimal disturbance as compared to other coring methods.

2.4 Introduction

High-resolution temporal records are invaluable to paleoenvironmental reconstructions in the fields of paleolimnology and paleoceanography (Kulbe & Niederreiter jr 2003; Blass et al. 2007). Climate cycles and oscillations (El Niño/Southern Oscillation, Pacific Decadal Oscillation, various solar cycles) archived within lake sediments, require a sub-decadal sampling resolution in order to be recognized (Renberg 1990; Patterson et al. 2004; Chang & Patterson 2005; Patterson et al. 2007; McKay et al. 2008). High-resolution studies of anthropogenic impact are also necessary to establish the degree of environmental alteration and monitor restoration efforts (Smol 1995). Unfortunately, most suitable lacustrine (Gasirowski 2008) and marine (Reading 1996) systems are characterized by low sedimentation rates, where the standard core subsampling resolution of 0.5-10 cm is typically insufficient to detect many important paleoclimate and paleoenvironmental signals (Patterson 1993).

In this paper we describe the construction and application of a custom designed sledge freeze core microtome designed for precise and accurate millimeter to submillimeter-scale core sampling of freeze cores. The impetus for the development of this device was the mm-scale subsampling strategy required to examine sediment cores at decadal to sub-decadal resolution. Our device is specifically designed to subsample freeze cores, which are ideally suited for the recovery of high quality sedimentary sequences (Lotter et al. 1997; Kulbe & Niederreiter jr 2003; Blass et al. 2007). This sampling capability extends to the generally highly unconsolidated and water saturated sediment near the water interface, which is difficult to recover undisturbed using most other corers (Lotter et al. 1997; Kulbe & Niederreiter jr 2003; Blass et al. 2007).

The use of cryo-chambered sledge microtomes in various biomedical disciplines has been long established and these commercially available instruments can produce serial sections down to only a few microns thick. However, even the largest of these devices are only satisfactory for sectioning objects in the mouse size range, and they are very expensive. More applicable to sedimentological applications, Cocquyt and Israe (2004) developed a custom microtome for high precision subsampling of certain soft sediment cores, at mm resolution. That instrument is unfortunately not suitable for slicing freeze cores, and is incapable of subsampling the soupy sediments that characterize the sediment-water interface and upper portions of many lacustrine cores without application of a dewatering procedure (Cocquyt & Israe 2004).

2.5 Description

The sledge freeze core microtome (Appendix B.1 - Illustrations B.1.1-3) is constructed of aluminum and composed of two main parts, a table assembly (a) and a sediment cutter assembly (e-m). The table assembly has two parts; a metal ramp (a), and a polyethylene plastic cutting board (b) which snaps onto the metal ramp (d). Spaced at regular intervals along the cutting board are height-adjustable brass spikes (c) that help fix the core to the cutting board. The bottom of the cutting board is also equipped with clips (d) that facilitate the quick exchange of boards, so one can slice another section of the core while a previous section is frozen again.

The sediment cutter assembly is composed of the knife holder (e), the knife holder pivot system (f), two rods for vertical movement (g) and the crank system (h-i) used to move the knife horizontally. A ceramic blade (n) is used since it is the sharpest available and also avoids any potential contamination issues associated with using a metal blade. The blade is secured by several nylon screws, permitting the easy removal of the blade for cleaning or storage. The knife holder is attached to two round pivots (f). Each pivot is attached to a rod (g), thus the pivots can be moved vertically simultaneously to raise the knife, or one at a time to raise or lower either end of the knife. The pivots also allow the knife to be moved in a pendulum motion perpendicular to the cutting board. This swinging ability extends the blade's cutting range and allows the researcher to rock the knife while slicing, greatly facilitating the process. The knife holder, the pivots and the rods are all suspended from the crank system (h-i). The crank system uses a bolt (i) with a pitch of 2 mm per revolution of the crank wheel (h). Notches around the circumference of

the crank wheel (h) are calibrated to 0.2 mm movements of the knife along the cutting board. This allows the researcher to choose the desired slice thickness greater than or equal to 0.2 mm. A metal foot (j) that spans the base of the two pivot rods considerably reduces play within the pivot and rod system. Some play is present at the base of the blade (<0.5 mm), but with practice and careful use precise and accurate cuts can be consistently achieved.

The feet (k) of the sediment cutter assembly fit onto the top of the metal ramp (a) (Illustrations 1 & 3). Small holes drilled along one side of the metal ramp allow for a pin (l) in one of the legs of the sediment cutter assembly to fit inside, adding stability while cutting. Small vice screws (m) in each foot of the sediment cutter assembly are then tightened to secure them to the metal ramp.

2.6 Operation of the Microtome

As the name suggests, the sledge freeze core microtome is primarily designed to be used with freeze cores, although the instrument could be used for cutting any stiff sediment. Limits imposed on the size of the core are due to the height of the blade and the area that the blade can be rocked widthwise to cover. It is assumed that the freeze core sections will have a flat face (the face that was directly touching the freeze corer). The flat face is resting on the cutting board surface. The microtome can accommodate cores that are a maximum of 3.5 cm in height off the cutting board surface and a maximum of 19.5 cm in width. All cores that we deal with within our laboratory are massive in structure. The great benefit of this apparatus is the quickness with which a freeze core can be

subsampled at millimeter intervals. With laminated sediment where the laminae are tilted width wise. It is possible to detach the cutting board from the ramp and rotate it to the desired orientation. This will add time to the procedure though.

As cores to be cut will be subsampled at high resolution it is extremely important that the core is not moved during processing. For best results the core is fastened to the cutting board using plastic wrap and tape and further stabilized using the adjustable brass spikes (c). A block (o) is also placed against the end of the core segment (p) furthest from the blade and clamped down to further immobilize the core during cutting.

It is very important that cores be at the right temperature before subsampling to ensure best results. To use a familiar analogy, freeze cores are similar to ice cream in consistency. When ice cream is frozen solid it is very difficult to obtain scoops and when it is too soft the results are similarly unsatisfactory. Accurately subsampling a completely frozen freeze core just removed from our -10°C cold room is very difficult as it is difficult for even a ceramic knife to penetrate the sediment. Freeze cores must therefore be warmed slightly prior to cutting. In our facility a core to be cut is moved from the cold room to a 4°C cool room for 30 minutes. A core can be subsampled in this environment for ~ 90 minutes before it must be returned to the cold room. Each sediment slice is collected using a small spatula, which is used to push the slice into a vial held beside the cutting board. As long as the core has not been allowed to thaw too much, no sediment is lost on the knife blade or the cutting board surface. Two sets of measurements are taken regularly to ensure slicing precision and accuracy. A piece of

tape runs the length of the core, and a straight line is drawn down its length allowing for the precise placement of the ruler during every measure. An absolute measure of the entire core length is taken, as well as a relative measure (the length from the edge of the cut face to a mark along the length of the tape).

A practical concern with this instrument is the stabilization of very short cores (less than 1 cm in length) as these cores are too small to be stabilized with plastic wrap and tape. When such a core is cut the furthest end from the knife tends to lift or may fracture into many pieces widthwise. This problem was solved by permitting the core to come up to a higher than normal cutting temperature so that there is less resistance against the knife. Cleaning the instrument between samples becomes very important when dealing with these very small segments. The help of an assistant is also beneficial when dealing with short core segments as the assistant can manually hold the core in place with metal spatulas. The use of fingers or hands to hold short cores in place is strongly discouraged as ceramic knives are capable of producing nasty cuts.

Presently many concurrent studies are employing the device in our lab and have no difficulty consistently slicing freeze cores at 1 mm resolution, noting no sediment loss or loss of precision due to cutting inaccuracy.

2.7 Conclusion

We describe a sledge microtome designed for the high-resolution subsampling of freeze cores. We present not only instructions on its use but a detailed summary of its design so that others can construct this inexpensive freeze-core microtome. Such a subsampling resolution permits recognition of sub-decadal to annual events even in systems with low sedimentation rates.

The main goal of this project and my thesis is to better constrain natural climate variability for the central Northwest Territories, this includes better understanding the rate of environmental responses to climate variability. The microtome enabled us to increase the temporal resolution from centennial to multi-decadal and even in some lakes to sub-decadal. It has served as a published manual for future researchers in our lab as they continue to use the machine to this day.

We follow this chapter with a practical application of the microtome on two lakes Danny's Lake and Carleton Lake. We seek to test the value of grain-size analysis, specifically end-member mixing analysis. We showcase how it can be used to track the environmentally variability of the Holocene. If we had used a traditional sub-sampling approach of 0.5 cm on the Danny's Lake core this would have resulted in a temporal resolution of 20-60 years per data point, while a 0.1 cm sub-sampling interval resulted in a temporal resolution of 4-12 years per subsample. This has allowed us to track the 8.2 ka cooling event that is only 200-300 years in length with unparalleled resolution for this area.

3 Chapter: End-member mixing analysis of lake sediment grain-size distributions for reconstructing Holocene paleoclimate variability in the Canadian Subarctic.

3.1 Authors & Addresses

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3.2 Foreword

This chapter demonstrates the utility of end-member mixing analysis of lake grain-size distributions to track Holocene climate variability in the central Northwest Territories. Previous work has shown that lake sediments are associated with the melt-water equivalency of the spring freshet (Francus et al. 2002; Cockburn & Lamoureux 2008a; Cockburn & Lamoureux 2008b; Francus et al. 2008). Issues arise in being able to target specific grain-size components of depositional processes thus allowing for the reconstruction of Holocene climate variability. End-member mixing analysis aims to provide genetic interpretation of multi-modal grain-size distributions with minimal assumptions (Weltje & Prins 2003; Weltje & Prins 2007; Dietze et al. 2012). The results presented here show that primary factors controlling hydraulic energy include: density of catchment vegetation, ratio of winter to summer precipitation and sediment availability; and recognize climate amelioration during the Holocene Climate Optimum and the climate deterioration associated with onset of the Neoglacial cooling at 2600 cal yBP. This has important implications for future research as the combination of EMMA and the sledge microtome (Chapter 2) will allow for time series analysis at a sufficient temporal resolution to identify decadal and multi-decadal climate modes of variability that have modulated the regional climate over the last 8000 years.

3.3 Abstract

Lake sediments of the central Canadian Subarctic, specifically the northern treeline region, archive valuable proxies of Holocene climate variability. Due to complex interactions between climate and climate proxies, it is important to evaluate as many proxies as possible in order to produce a robust and coherent paleohistory. A new and promising proxy candidate is end-member mixing analysis of grain-size components of lacustrine sediments, which can provide an important source of information about changes in regional hydrology and global atmospheric circulation. End-member mixing analysis of three independent datasets of lake grain-size distributions, including a modern training set and two sediment cores, detected two end-members present in all three datasets: an offshore suspension load end-member and a spring overflow end-member. The end-members were successfully used to reconstruct climate variability associated with the 8200 cal yBP hemispheric cooling event, which was triggered by the rapid northward drainage of the super lake formed by the glacial lakes Agassiz and Ojibway. They also tracked hydrologic changes associated with changing vegetation cover in the catchment due to climate amelioration during the Holocene Climate Optimum at *ca.* 5500 cal yBP and climate deterioration associated with the onset of the Neoglacial Cooling at 2600 cal yBP. Our findings demonstrate the utility of end-member mixing analysis of grain-size distributions as a proxy for climate variability.

3.4 Introduction

3.4.1 Sensitivity of the Canadian Subarctic to climate variability

The central Northwest Territories is a low lying interior plain referred to as the northern treeline, which includes the taiga, the tundra and the transition between the two. Although the focus is only on the Canadian Subarctic, the taiga biome is the largest terrestrial biome on Earth, and thus of global relevance. The Arctic is sensitive to current climate variability and a key region of the world for understanding the climate system because most fauna and flora are living at or near their ecological thresholds. The Canadian Subarctic of the central Northwest Territories (Appendix C.1 - Illustration C.1.1) has undergone tremendous change during the recent climate changes and has experienced some of the most rapid warming in the Northern Hemisphere ($\sim 1.5\text{-}2.0\text{ }^{\circ}\text{C/decade}$ from 1966 -2003; ACIA 2005). The warming trend since the late 1800s has left the Arctic warmer than at any time in the preceding 2000 years (Walsh et al. 2012; Upiter et al. 2014). However the instrumental climate record for the Arctic is limited. Few instrumental records exist and they only cover the period post-1950, too short to study most climate phenomena. The closest instrumental meteorological record is found in the City of Yellowknife making quantification of natural climate variability for this remote region difficult (ACIA 2005). Thus researchers must rely on proxy records to get a sense of the range of past climate variability (Bradley 1999).

3.4.2 Lakes are abundant and sensitive to climate

With open water accounting for about 25% of the study area (Spence & Woo 2008), the abundance of lakes in the Northwest Territories represents a valuable resource for the

reconstruction of regional paleoclimate. Freeze-up and breakup dates that bracket the duration of ice cover have been shown to be robust indicators of climate variability (Rouse et al. 2008). The high sensitivity of these treeline lakes to catchment processes can be attributed to their chemically dilute nature and their position at a major ecotonal boundary (Pienitz et al. 1999). Lakes often contain continuous sedimentary archives of biological, chemical and physical proxies of environmental conditions that have been influenced by broad-scale patterns of Holocene natural climate variability (MacDonald et al. 1993; Wolfe et al. 1996; Pienitz et al. 1999; MacDonald et al. 2009; Rühland & Smol 2005; Moser & MacDonald 1990; Huang et al. 2004; Paul et al. 2010; Upiter et al. 2014).

3.4.3 Lake sediments as potential proxies of climate variability

Multiple proxies must be investigated concurrently to produce a robust and coherent climate history due to the complex interactions among parameters within natural systems. However, little attention has been paid to the portioning of grain-size components in lacustrine sediments in this region. Yet clastic materials deposited in lakes potentially provide an important source of information about changes in regional hydrology and global atmospheric circulation (Xiao et al. 2012; Francus et al. 2002; Sun et al. 2002; Chen et al. 2004; Cockburn & Lamoureux 2008a; Conroy et al. 2008; Kirby et al. 2010). Lake catchments undergo constant alteration by exogenic forces such as weathering, erosion and deposition (Håkanson & Jansson 1983). The grain-size frequency distribution (GSD) of a sample of lake sediment can provide insight into exogenic processes responsible for the deposition of sediment onto the lake bottom (IJmker et al. 2012), because a relationship exists between clastic and hydraulic interactions within a lake and

its catchment (Chen et al. 2004; Sun et al. 2002; Conroy et al. 2008; Kirby et al. 2010; Francus et al. 2002). Grain-size distributions generally become coarser as the hydraulic energy within a lake-catchment system increases (Sly 1989; Xiao et al. 2012), and finer as it decreases (Chen et al. 2004). In their study of Lake Erhai (Chen et al. 2004) found that studies of GSDs that have at least a multi-decadal resolution are able to track rainfall changes. Francus et al. (2002) found that snowmelt intensity, an index reflecting the hydraulic energy available for sediment transport, impacts the 10-20 and 20-60 μm sediment fractions and that higher proportions of fine silt correlates to low intensity summer precipitation. Thus GSDs of lake sediments represent a target for constraining historical climate variability. Cockburn and Lamoureux (2008b) cautioned against using basic grain-size parameters such as mean grain size to interpret hydrologic signals within lake sediment cores as there is strong evidence for substantial decoupling between deposition rate and mean grain size of sedimentary. They also suggested that a targeted approach (i.e. the coarser fraction) rather than the bulk sediment, may be more appropriate to use as a link between contemporary runoff process and sedimentary characteristics (Cockburn & Lamoureux 2008b).

3.4.4 Application of end-member mixing analysis to GSDs

Grain-size distributions are often multimodal due to modification of the sediment inflow signal through redistribution prior to ultimate deposition of sediments (Dietze et al. 2014; Cockburn & Lamoureux 2008b). Multimodal distributions are made up of dynamic subpopulations that were sorted by different sediment production, transport and accumulation processes (Doeglas 1946; Weltje & Prins 2007). A robust statistical

procedure must be applied to GSD data to separate their original subpopulations (Dietze et al. 2014). A summary of various techniques is given by IJmker et al. (2012). End-member mixing analysis (EMMA) is a new and promising methodology. EMMA is based on the principles of factor analysis and principle component analysis and extracts end members from the eigenspace of a dataset. Each end-member (EM) consists of loadings and scores. Loadings represent the EM in the variable space as seen by its frequency distribution in grain-size classes. Scores are the contribution made by the EM to each sample. EMMA aims to provide a genetic interpretation of GSDs with minimal assumptions (Weltje & Prins 2003; Weltje & Prins 2007; Dietze et al. 2012) and was first extensively described by Weltje (1997). EMMA uses all available samples from a certain archive and unmixes the subpopulations (Dietze et al. 2014). Each EM is thought to represent a specific depositional process. Some depositional processes can be linked to lake-catchment hydraulic energy and thus reflect a climate dependent process. Recent examples of EMMA of sedimentological data include: the study of dust supply to the Chinese Loess Plateau (Prins et al. 2009), and; transport processes within the Donggi Cona lake catchment (Dietze et al. 2012; IJmker et al. 2012) and across the Tibetan Plateau (Dietze et al. 2014).

In this study EMMA is applied to three independent datasets of lake grain-size distributions to look for similar EMs in order to distinguish the main detrital processes contributing to lacustrine sedimentation in the central Northwest Territories.

3.5 Catchment-Lake Dynamics

3.5.1 Geography and Geomorphology of the Region

Pleistocene glaciation scoured the Canadian Shield to expose Precambrian gneissic and granitoid rocks in the central Slave Geologic Province. This glacial action produced a rolling topography of undulating bedrock uplands, soil mantled slopes and soil-filled valleys that often contain wetlands and lakes. Glaciofluvial deposits in the forms of drumlins, eskers and deltas appear throughout the physiographic province (Spence & Woo 2008). Soils are poorly developed with discontinuous permafrost south of the treeline and continuous permafrost north of the treeline (Spence & Woo 2008). The present-day treeline runs NW/SE across the study area, roughly delineating the polar front (Figure 1 Appendix C.1 - Illustration C.1.1 ; Huang, MacDonald, and Cwynar 2004) and is marked where forest stands are open and lichen woodlands merge into areas of shrub tundra (Galloway et al. 2010).

3.5.2 Paleoclimate of the Region

Previous paleoclimate reconstructions have identified three main stages of landscape development. The first stage occurred between ~8500 cal yBP and 6300 cal yBP when birch dominated shrub tundra transitioned to spruce forest tundra following regional

deglaciation (Huang et al. 2004). At ca. 8200 BP a hemispheric cooling event occurred, triggered by the rapid northward drainage of the super lake formed by the glacial Lakes Agassiz and Ojibway (Clarke et al. 2004). This cold event is represented in the GRIP and GISP ice cores from Greenland and was the most significant climate excursion of the past 10,000 years (Clarke et al. 2004). During this roughly 200-year interval mean temperature is thought to have dropped by as much as 3-5°C (Clarke et al. 2004). The second stage was marked by a rapid forest expansion to about 50 km north of the present day treeline, likely reflecting a northward movement of the polar front between ~6300 and 3000 cal yBP (Moser & MacDonald 1990; MacDonald et al. 1993; Huang et al. 2004). The final stage began with the onset of the Holocene Neoglacial when cooling at 3000 cal yBP resulted in southward retreat of treeline to its current position (Huang et al. 2004).

The present climate of the region is continental, characterized by short summers and long cold winters. Annual precipitation is low (175 – 200 mm) and mean daily January temperatures range from -17.5°C to -27.5°C, while mean daily July temperatures range from 7.5°C to 17.5°C (Upiter et al. 2014). Annual snow cover forms in October and lasts until the end of April or beginning of May when the open water period and vigorous energy cycle of the small lakes begins (Spence & Woo 2008; Rouse et al. 2008).

3.5.3 Hydrology of the Region, with a focus on lakes

The hydraulic model proposed by Cockburn and Lamoureux (2008a), Francus et al. (2008) and Spence and Woo (2008) is adopted for these lakes. Snowmelt during the

spring is the main source of water for hydraulic energy and the dominant factor in controlling total suspended sediment transfer within the catchments of lakes in the central Northwest Territories (Spence & Woo 2008; Mielko & Woo 2006; Cockburn & Lamoureux 2008a). Secondary factors include melt energy, snow distribution and sediment supply (Cockburn & Lamoureux 2008a). Several factors affect the movement of water through the catchment. The presence of fracture networks in upslope bedrock, soil cover and soil depth serve to reduce surface runoff (Mielko & Woo 2006; Spence & Woo 2008). Infiltration is limited where concrete frost is present, as in most valley wetlands (Spence & Woo 2008).

During the first week of sustained meltwater flow, cold streams with low concentrations of suspended sediments enter the lake (Francus et al. 2008; Cockburn & Lamoureux 2008a). The lake water is warmer than the meltwater and this thermal contrast produces overflow conditions. Overflows dominate the dispersal pattern as cold, near-freezing meltwaters with low sediment concentrations flow in the upper 2 meters of the water column beneath the lake ice cover (Cockburn & Lamoureux 2008a). Cockburn and Lamoureux (2008b) found that delivery of coarse sediment to the lake bottom occurred during intense inflow due to rapid runoff of snowpack melt. After snowmelt, greater ground infiltration and evaporative loss reduced hydraulic energy associated with summer rainfall events (Spence & Woo 2008) and finer grains are deposited through much of the remaining season (Cockburn & Lamoureux 2008b). Large autumn rainfall events have the potential to generate hydraulic energy but must exceed the storage capacity of the catchment (Spence & Woo 2008).

3.6 Methods

3.6.1 Modern Training Set

Samples were collected as part of a NSERC Strategic Grant mandated to better understand the climate variability in the central Northwest Territories (Galloway et al. 2010; Macumber et al. 2012). The training set consists of fifty-seven lakes sampled in August of 2012. A spatial survey of lakes in the study area was an important precondition for extracting climate signals from sediments because it shed light on lake settings that the robust EMs (rEMs) were associated with (Dietze et al. 2012). Samples were taken as 0.5 cm thick skims of sediments at the sediment/water interface obtained using an Ekman grab sampler. During sediment collection, water column properties were measured with a portable multiparameter instrument: depth (m), pH, dissolved oxygen (%), temperature (°C), conductivity (µs), and physical parameters were noted as well: Northing, surface area (m²).

3.6.2 The Cores

Cores were collected by deploying a freeze corer through augured holes in lake ice (Galloway et al. 2010; Macumber et al. 2012; Lotter et al. 1997; Glew et al. 2001; Kulbe & Niederreiter jr 2003; Blass et al. 2007). Cores were sub-sampled at mm-scale intervals using a custom designed sledge microtome (Macumber et al. 2011).

Danny's Lake is located 40 km southwest of the modern treeline (Appendix C.1 – Illustration C.1.1; Appendix C.2 - Table C.2.1). It is a small, cold polymictic lake that

was well mixed in August and March (Appendix C.2 - Table C.2.2). The surface area of the catchment that transfers hydraulic energy to the lake was estimated using the elevation and distance tools found in Google Earth (v. 7.1.2.2041) (Appendix C.2 - Table C.2.1). The lake is surrounded by gently sloping hills with local highs to the northwest and east. Discontinuous permafrost exists in the region (Natural Resources Canada 2009). Danny's lake has two sub-basins; a shallow basin with a gradual slope and a larger northern sub-basin (Appendix C.1 – Illustration C.1.2). In March 2010 a 115 cm sediment core was collected from Danny's Lake including the sediment-water interface (Appendix C.2 – Table C.2.3). The core was massive and made up of fine organic mud. X-Ray analysis revealed no internal structure apart from a density change that coincided with a distinct colour change at roughly a meter core depth (Macumber et al. 2012).

Carleton Lake is located 120 km north of the present day treeline (Appendix C.1 – Illustration C.1.1; Appendix C.2 - Table C.2.1). Like Danny's Lake, it is a small cold polymictic lake that is well mixed year round (Appendix C.2 - Table C.2.2). The surface area of the catchment that transfers hydraulic energy to the lake was estimated using the elevation and distance tools found in Google Earth (v. 7.1.2.2041) (Appendix C.2 - Table C.2.1). Upslope areas lie in close proximity to the north and northwest. Lowland areas lie to the east and south. Carleton Lake occurs within an area of continuous permafrost but lies close to extensive discontinuous permafrost (Natural Resources Canada 2009).

Detailed bathymetry was made available courtesy of Tetra Tech EBA (Appendix C.1 – Illustration C.1.2). In March 2012 a 110-cm sediment core, including the sediment water

interface, was retrieved from the northern end of Carleton Lake. The core was uniform in colour and massive in texture both visually and by x-ray imaging.

Detailed discussion of the obtained radiocarbon dates (Appendix C.2 – Table C.2.4) and derived age-depth models (Appendix C.1 – Illustration C.1.3) are available in (Crann et al. 2015). The Danny's lake core records a moderate sediment accumulation rate with a bi-modal deposition time frequency distribution, one mode centered around 50 yr/cm and the other around 100 yr/cm (Crann et al. 2015). The basal date of the core is 8390 cal yBP (Appendix C.1 – Illustration C.1.3). The Carleton lake core yielded a rapid accumulation rate with a unimodal deposition time frequency distribution centered around 20 yr/cm (Crann et al. 2015). The basal date of the core is 2810 cal yBP (Appendix C.1 – Illustration C.1.3).

3.6.3 Treatment of Subsamples

3.6.3.1 Laboratory Analysis

Grain-size distributions for 93 different grain-size classes, ranging from 0.4 to 2000 microns, were determined for every site and core sub-sample using a Beckman Coulter LS 13 320 Laser Diffraction-Particle Size Analyzer with a Universal Liquid Module. Utilizing a protocol modified from van Hengstum et al. (2007) and Murray (2002); 30% H₂O₂ was added to sub-samples in a 80°C water bath to oxidize organic matter. HCl treatment was deemed unnecessary since inorganic carbon content was insignificant. Training set subsamples were submitted for four acid digestion and were analyzed by ICP-MS for 57 elements by Acme Analytical Laboratories Ltd. Training set subsamples

were sent to the G.G. Hatch Stable Isotope Laboratory to measure the isotopic concentration of organic carbon and nitrogen, as well as their elemental abundance.

3.6.3.2 Data Handling

Four training set sub-samples that did not undergo grain-size analysis were excluded as were two sub-samples that contained anomalously high sand percentages. In the ICP-MS dataset seven sites had missing values and were omitted. Seven elements were removed due to high relative uncertainty ascertained by comparison with replicates. Values below detection were changed to a value of half the detection limit. Values above detection were change to the maximum detection value. Thirty-seven variables were ignored based on logical relevance and literature review. This left the following fifteen elements: Al, As, Cd, Cu, Fe, K, Mg, Mn, Na, Ni, P, Pb, S, Ti and Zn. Stable isotope and elemental analysis of training set sediment-water interface samples measured four parameters, of which only two (percent carbon and carbon:nitrogen) were kept. Within the stable isotope dataset three sites were missing values and were excluded from the study. This left 44 sites with 26 parameters for multivariate analysis. Compositional variables (e.g., ICP-MS dataset and the EMMA dataset) do not vary independently (Reimann et al. 2008) thus suffering from data closure. Data transformations were used to open the data and eliminate the effects of closure using either an additive log ratio (ICP-MS dataset; Ti) (Reimann et al. 2008). The EMMA data could not be opened due to a large number of structural zeros present. All datasets were tested for normality using the Shapiro-Wilks test in R (Team 2014), as issues can arise in multivariate statistics if variables are not symmetrical (Legendre & Birks 2012b). If non-normal they were transformed using a

box-cox transformation in R (Fox & Weisberg 2011; Legendre & Birks 2012b). Datasets were scaled and centered prior to multivariate analysis since they were not all expressed in the same physical units (Reimann et al. 2008; Legendre & Birks 2012b).

3.6.3.3 Statistical Analysis

Interdependence between variables was tested using either a Pearson product-moment correlation coefficient (i.e. for normality distributed variables) or a Kendall's rank correlation coefficient (i.e. for non-normal distributions). Cluster analysis and an exploratory principal component analysis (PCA) were used to identify redundancies within the selected parameters. Groups of highly interdependent variables were reduced to one representative member (Reimann et al. 2008). One of the main assumptions of multivariate analysis is that dimensionality is observed. With only 47 sites this could support roughly 6 parameters (Reimann et al. 2008). The R-Mode cluster analysis was carried out in R (Team 2014) using an unweighted pair group method with arithmetic mean hierarchical cluster method to look for breaks in the variance structure. Both cophenetic correlation and the Gower distance were used to select the cluster method that best represented the variance structure (Borcard et al. 2011). The Rousseeuw quality index and the Mantal statistic were used to define the number of clusters (Borcard et al. 2011). The vegan package (Oksanen et al. 2013) in R (Team 2014) was used to run the PCA. A final PCA with reduced parameters was used to examine the relationships between all measured lake parameters. It was hoped that the results would elucidate the types of environments associated with the rEMs. A detrended correspondence analysis showed that there was a gradient of less than 3 so the Euclidean distance used by PCA

was appropriate (Legendre & Birks 2012b). A broken stick model (Legendre & Birks 2012b) was used to determine the number of significant axes. For each significant ordination axes only those variables that had loadings greater/lesser than the mean plus/minus one standard deviation were considered of importance. PCA was done separately for each rEM to avoid closure issues due to the inability to open the rEM dataset. Issues associated with closure were evidenced in the Kendall τ ranked correlation analysis where rEMs showed strong negative correlations with one another.

3.6.4 End Member Mixing Analysis

EMMA was performed separately on each grain-size dataset. The procedure of Dietze et al. (2012) and Dietze et al. (2014) was followed using extensions implemented in the R package EMMAgeo (Dietze & Dietze 2013). Grain-size classes containing zero values in all sub-samples were excluded to avoid numerical instabilities. All samples were recalculated to the constant sum of 100% (Dietze et al. 2012). Only rEMs with non-overlapping, interpretable EM loadings were included, with the addition of those in which similar EM loadings occurred in most of the model runs (Dietze et al. 2014).

3.7 Results

3.7.1 Grain-size Analysis

Grain-size analysis results for each dataset can be seen in Illustration C.1.4 (Appendix C.1). Kendall's τ rank correlation of the datasets revealed clear statistical associations ($r > 0.9$) between adjacent fine grain-size classes, thus every two adjacent grain-size classes of less than 15 μm were summed up since these sizes are covered by a high density of

sensors (Dietze et al. 2012). No subsamples, apart from the two removed, contained grains greater than 1000 μm . This permitted the removal of the coarsest five grain-size bins (1000 – 2000 μm), reducing the number of variables from 93 to 66 and improving the variable to sample ratio to 66:51 (Dietze et al. 2012). The Danny's Lake grain-size record consisted of 558 subsamples. Only one subsample contained grains greater than 309 μm , thus values between 309 and 2500 μm were summed up to remove zeroes from the dataset. This improved the variable-to-sample ratio to 47:558. The Carleton Lake grain size record consisted of 169 subsamples. Adjacent grain-size classes greater than 133 μm were summed up since Kendall's τ coefficients revealed clear statistical associations ($r > 0.9$) between these grain-size bins. Only four subsamples contained grains greater than 309 μm so the values between 256 and 2500 μm were summed up to remove a great amount of zeroes from the dataset. This improved the variable-to-sample ratio to 47:169.

3.7.2 End Member Mixing Analysis

End-member mixing analysis identified several rEM within each dataset (Appendix C.1 – Illustration C.1.4). One can assess the robustness of the modeled EMs based on the size of their standard deviations ($\pm \sigma$) (Dietze et al. 2014). For example, the rEM of the training set and Carleton Lake datasets were more robust than those of the Danny's Lake dataset. Another feature of rEMs is the presence of smaller secondary modes that usually plot at the same position as the primary modes of other rEMs (Dietze et al. 2014). Dietze et al. (2014) suggests that they are merely artifacts of the EMMA. Robust EMs varied in both their presence/absence within the datasets and their abundance within

sites/subsamples (Appendix C.2 - Table C.2.6). EMMA of the training set samples produced four rEMs explaining 83% of the mean total variance (Appendix C.2 - Table C.2.6). These four rEMs were kept for multivariate analysis; fine silt modes (rEM-6.5 μ m & rEM-14 μ m), coarse silt mode (rEM-70 μ m) and fine sand mode (rEM-161 μ m). Three rEMs occurred in the Danny's Lake dataset explaining 91% of the mean total variance. Two rEMs occurred in the Carleton lake dataset explaining 84% of the mean total variance.

3.7.3 Dependence Tests

The results of dependence tests are shown in Table C.2.7 (Appendix C.2). Variables that showed a significant level of interdependence ($p < 0.05$) were candidates for removal so as to reduce redundancy in the biplots. Dependence tests were successful in reducing the number of variables from 26 to 10. For example, conductivity and Northing share greater than 50% of their variance so only conductivity was kept because the tree-line is not perfectly North-South, instead running northwest so that conductivity might better reflect tundra vs. taiga sites. TOC showed significant interdependence with the elements Cd, Cu, Ni, Pb, P, S and Zn and was thus used as proxy for them. Another strong set of interdependent variables is related to total organic carbon vs. minerogenics, which are inversely correlated. This relationship can be recognized in the negative association of TOC and K, which explain 30% of their variance. K was excluded from the study, but it should be noted that it shares 50% of its variance with Na that was kept. Na also shares 30% of its variance with Al. Na was kept as a proxy for K and Al. Both Fe and Mn shared greater than 50% of their variance thus only Fe was kept.

3.7.4 Cluster Analysis

R-mode cluster analysis of the ten environmental parameters and the four rEMs produced three clusters. The first cluster contained rEM-70 μ m, rEM-161 μ m and Na. The second cluster contained the rEM-14 μ m, dissolved oxygen, As, Fe, C:N, TOC and conductivity. The final cluster contained the rEM-6.5 μ m, Mg, surface area and depth. Q-mode cluster analysis of rEMs and sites generated five clusters. Q-mode cluster analysis did not discriminate between tundra vs. taiga sites or between on-road vs. off-road sites.

3.7.5 Principal Component Analysis

The preliminary PCAs consisted of ten environmental parameters and one of the rEMs. Robust EM-14 μ m was poorly constrained by the PCA and did not show any strong relationships with any of the principal components. It was assumed that the model poorly constrained the variance of rEM-14 μ m and it was excluded from further multivariate analysis. The concentration of As was poorly constrained by all three PCAs and was excluded from further analysis (Borcard et al. 2011). Robust EM-6.5 μ m did not show a strong relationship with surface area, Fe or Mg. Robust EM-70 μ m showed no association with surface area, Mg, total organic carbon or C:N. Robust EM-161 μ m did not show any association with Fe, Mg, or conductivity.

The final PCA contained six environmental parameters for rEM-6.5 μ m and rEM-161 μ m and five parameters for rEM-70 μ m. Both rEM-6.5 μ m and rEM-70 μ m have positive associations with oxygenated sites (Appendix C.2 - Table C.2.6; PC3-6.5 μ m; PC1-70

μm). In the case of rEM-6.5μm these sites tend to also be characterized by low conductivity (PC3), while for rEM-70μm the sites tend to be shallow and reduced in Fe (PC1). Some sites with reduced dissolved oxygen are also shallow with low C:N values (PC3-161 μm) or reduced Na values (PC2-70 μm). Robust EM-6.5μm shows a negative association with Na (PC2), while rEM-161μm has a positive association (PC2). Robust EM-70μm (PC1) and rEM-161μm (PC2) are negatively associated with deep lakes. With regards to rEM-70μm these sites are well oxygenated and show reduced Fe concentrations (PC1), while for rEM-161μm the lakes tend to have small surface areas and are shallow with increased concentrations of Na (PC2). Some deep lakes have lower conductivities (PC3-70 μm) or lower total organic carbon concentrations and reduced C:N values (PC1-6.5 μm; PC1-161 μm).

3.7.6 End Member Description

3.7.6.1 Overflow

Robust EMs with primary modes within the coarse silt to fine sand range (i.e. 31-250 μm) are interpreted as overflow deposits contributed by spring meltwater and herein referred to as rEM-Overflow. Robust EM with a fine sand mode in the Danny's Lake dataset will be referred to as the coarser rEM-Overflow. Cockburn and Lamoureux (2008b) found that sedimentary layers consisting of coarser sediment in West Lake were a reasonable proxy for melt and runoff intensity, which in turn were dependent on snowpack and melt conditions. Years with reduced delivery of coarse sediment in the proximal location were indicative of weak underflow activity (Cockburn & Lamoureux 2008a). Rain events during the summer season were insufficient to move this type of

material (Spence & Woo 2008). In the Danny's Lake dataset a rEM with a coarse silt mode comprised greater than 80% of the sub-samples. Half of the lakes within the training set contained a rEM with a very fine sand mode. All three datasets contained a rEM with a fine sand mode (Appendix C.2 - Table C.2.6).

Results of a multivariate analysis of the training set parameters support our identification of rEM-Overflow. The R-mode cluster analysis binned rEM-70 μ m and rEM-161 μ m together. Both are associated with Na (Appendix C.1 – Illustration C.1.4; PCA) and Al (Appendix C.2 - Table C.2.8). The three elements Na, Al and K show strong interdependencies (Appendix C.2 - Table C.2.8) and we interpret their compositions as being related to the influx of detrital igneous clasts being washed in from the catchment (MacDonald et al. 1993). This interpretation is further supported by the negative correlation K with TOC (Appendix C.2 - Table C.2.8). The Carleton Lake rEM with a fine sand mode spans the range from 40-200 μ m. This range encapsulates the Danny's Lake rEM with a coarse silt mode, the training set rEM-70 μ m and rEM-161 μ m seen in all three datasets. We interpret this as significant as it shows that there is a range of sizes associated with this type of deposit. Xiao et al. (2012) in their study of Hulun Lake in Inner Mongolia described a component with a mode of 65.7 to 160.7 μ m and a negative relationship to both water depth and distance from shoreline that was correlated with increased hydraulic energy due to precipitation events. Robust EM-70 μ m is negatively associated with sites that are both deep and found in larger lakes. Xiao et al. (2012) found a negative correlation of the 65.7 to 160.7 μ m component to both depth and distance to shoreline, and interpreted this component as a proxy of near shore or shallow environments. We feel that it is more accurate to associate these components with sites

that receive little to no direct input from catchment surface runoff. This interpretation is further supported by: positive associations of these sites with low C:N ratios values that reflect a greater percentage of algal plant relative to terrestrial derived carbon, and; negative associations of these sites with dissolved oxygen that reflects less circulation and positive associations with elevated Fe that reflect redox conditions.

3.7.6.2 Suspended Load

We interpret rEMs with fine silt modes to represent offshore suspension derived from low amplitude summer time precipitation and will refer to them as rEM-Suspended. Francus et al. (2002) found that the fine silt fraction (4-10 μm) was positively correlated with periods of frequent but low intensity summer (i.e. May to September) precipitation. A rEM-Suspended was found in all three datasets (Appendix C.1 – Illustration C.1.6). This rEM is found in the majority of training set sites and dominates the Carleton lake record (Appendix C.2 - Table C.2.6) and dominates the base of the Danny's lake record, but does not exceed abundances of 20% towards the top of the Danny's Lake core. The highest concentrations of this widespread rEM are positively associated with deep sites, organics of algae origin (Appendix C.2 - Table C.2.7) and low percentages of clastic minerogenics (Table C.2.7 & C.2.8). Xiao et al. (2012) similarly described a component ranging from 3 to 9 μm that was positively associated with depth, which they attributed to offshore suspension. Sun et al. (2002) described a component with a modal grain size of 8-9 μm that they interpreted as suspended load due to surface run-off during precipitation. This type of sediment is deposited through much of the season and can dilute the record, adding importance to our use of EM mixing analysis to discriminate components within grain-size distributions (Cockburn & Lamoureux 2008b).

3.8 Discussion

3.8.1 Case Study

3.8.1.1 Early Holocene

From the base of the Danny's Lake record to *ca.* 7500 cal yBP, apart from an interval associated with the 8.2 kyr event (see below), rEM-Suspended is the only component (Appendix C.1 - Illustration C.1.6). This is in stark contrast to the subsequent record where rEM-Overflow is the dominant component. The average sedimentation rate is 0.2 ± 0.04 mm/yr through this period with a step drop beginning *ca.* 7700 cal yBP to an average of 0.18 ± 0.05 mm/yr (Crann et al. 2015). There are several factors that could contribute to the predominance of rEM-Suspended. A pollen analysis of the Danny's Lake record (Sulphur, in prep) revealed a vegetated catchment reflective of a warm, dry climate free of permafrost. Although permafrost degradation may have increased sediment availability (Cockburn & Lamoureux 2008a), the drier climate and greater infiltration would have reduced the hydraulic energy of surface runoff events. The Early Holocene was also characterized by a higher summer to winter precipitation ratio of 65:35 as opposed to the modern value of 55:45 (Edwards et al. 1996), which would have increased the contribution of rEM-Suspended. Glacial clay was probably abundant within the catchment of the lake and represented the primary sediment provenance (Huang et al. 2004).

At 8200 cal yBP we see the first appearance of rEM-Overflow (Appendix C.1 - Illustration C.1.6). This is followed by an interval of 150 years where rEM-Overflow

peaks at $25 \pm 2\%$. We interpret this interval as being associated with the 8200 BP hemispheric cooling event triggered by the rapid northward drainage of the super lake formed by the glacial Lakes Agassiz and Ojibway (Clarke et al. 2004). This interval was recognized at Lake TK-2 as a period with more extended ice cover, lower diatom counts and decreased organic matter (Paul et al. 2010). On the Faroe Islands two lakes showed increases in sedimentation rate and influx of sand (Andresen et al. 2006). Timing of the event at Lake TK-2 was only roughly coeval with the 8200 BP event. The timing of the first appearance of rEM-Overflow (8205 cal yBP) is coeval with the date reported in literature and of a similar length (~ 150 yr) to that estimated for the length of this period (200 yr). According to our record it took only thirty years for rEM-Overflow to reach its maximal abundance, but over 100 years for conditions to return to $100 \pm 3\%$ fine silt abundance. The cool period is thought to have led to the deterioration of the vegetation cover, leading to destabilization of soils and finally resulting in enhanced influx of minerogenic sediment (Paul et al. 2010; Andresen et al. 2006). Alternatively, the cooling resulted in higher winter precipitation that increased overflow conditions with which the coarse silt rEM is associated.

3.8.1.2 Reduction of rEM-Suspended

From ca. 7500-6500 cal yBP rEM-Suspended declined from an average abundance of $100 \pm 2\%$ to roughly $17 \pm 12\%$ of the record and was replaced by rEM-Overflow as the main component. The sedimentation rate similarly slowed down. This transition represents an increase in hydraulic energy within the catchment in order to bring in coarser grains and/or a reduction in the availability of this sediment type in the

catchment. At this time the Danny's Lake catchment, as well as much of the central Northwest Territories, was becoming more densely forested as a consequence of a much wetter climate (Wolfe et al. 1996; Huang, MacDonald, and Cwynar 2004; Paul, Rühland, and Smol 2010; Sulphur et al., in prep). Although a wetter climate could promote greater minerogenic soil erosion (Huang et al. 2004) seasonal differences in hydraulic energy would dictate the components that would benefit. An increase in vegetation may have reduced sediment availability and hydraulic energy for erosion during summer months (Spence & Woo 2008), explaining why we see a reduction in the amount of the fine silt rEM. The wetter climate may also have resulted in a larger snowpack, increasing the hydraulic energy (Spence & Woo 2008) available during the spring melt, which would have carried coarser sediment components (Francus et al. 2008). Development of peatlands and moist soil areas may have resulted in frozen lowland areas during the spring that would preclude infiltration and facilitate surface runoff (Spence & Woo 2008). During this entire interval the summer to winter precipitation ratio was gradually lowering towards more modern values (Edwards et al. 1996). As a result the establishment of the modern day scenario where overflow deposits due to spring melt are the predominant source of sediment to the lake became established. Those intervals that include the coarser rEM-Overflow represent intervals with especially high hydraulic energy and thus might reflect greater winter precipitation.

3.8.1.3 Holocene Climate Optimum

In the Danny's Lake record from ca. 6500 to 5500 cal yBP rEM-Suspended exhibits an oscillating pattern of consistent amplitude with an average abundance of $17 \pm 11\%$ (Appendix C.1 - Illustration C.1.6). Sedimentation rates were relatively stable, from 7000

to 5400 cal yBP, averaging 0.12 ± 0.02 mm/yr (Crann et al. 2015). At this stage in the history of Danny's Lake summer precipitation was a greater contributor of sediment than later in the record, but spring melt overflow conditions dominated the sedimentary record. We do not attribute our results to lake shallowing, in which case we would have expected to see little to no rEM-Suspended as this component due to reworking. Instead this result supports our interpretation of the seasonal character of the sedimentation. Between 5880 and 1875 cal yBP we do not see the coarser rEM-Overflow in the Danny's Lake record. This reflects a reduction in the available hydraulic energy or a reduction in the availability of this sediment type. A reduced availability of the coarser rEM-Overflow would be likely with increased vegetation cover leading to reduced erosion in the catchment. Movement of the treeline to as much as 280 km north of its modern position around 5000 years BP has been documented in many studies of modern tundra lakes (MacDonald et al. 1993; Upiter et al. 2014; Edwards et al. 1996; Moser & MacDonald 1990; Pienitz et al. 1999; Paul et al. 2010). The treeline migration is believed to be due to a northward shift of the Arctic frontal zone at *ca.* 5000 BP in central Canada that would have produced warmer and moister conditions due to strong Pacific air mass influence in summer (Pienitz et al. 1999). That we see sedimentary evidence of increased vegetation cover earlier than previous studies can be attributed to Danny's Lake's position being further south. Wolfe et al. (1996) suggests that there were several episodes of treeline migration and that they usually coincided with increased inflow:evaporation ratios within the lake (6500, 5000, 4500, 3500, and 2400 BP). These intervals correspond with minima in rEM-Suspended and likely represent the greater hydraulic energy available at these times. Around 5500 cal yBP the amplitude of the oscillating pattern of rEM-Suspended

decreased to an average of $6\pm 6\%$ and sedimentation rate fell to its lowest levels with an average of 0.09 ± 0.02 mm/yr, persisting until *ca.* 4300 cal yBP. By *ca.* 5000 cal yBP summer to winter precipitation ratio had reached the modern value of 55:45 (Edwards et al. 1996) and the grain-size record reflects this with a further reduction in the average abundance of the fine silt component. The warming climate likely impacted permafrost deepening the active layer, increasing infiltration and making surface flow less likely during summer time precipitation events.

3.8.1.4 Neoglacial Cooling

After *ca.* 2600 cal yBP in the Danny's Lake record, there was a gradual decline in the amplitude of rEM-Suspended oscillations, reaching an average of $2\pm 3\%$ from 2250 cal yBP to the end of the record (Appendix C.1 - Illustration C.1.6). We interpret this interval as reflecting the gradual onset of Neoglacial cooling (Paul et al. 2010). The further reduction in the fine silt component could indicate a decrease in the amount of sediment eroded during summer time precipitation due to shorter summer seasons and/or deterioration of vegetation in the catchment making more sediment, including coarser material, available for erosion. After *ca.* 2200-2320 cal yBP palynological accumulation rates fell, indicating decreased vegetation surrounding the lake (Sulphur et al, in prep). In more northerly sites decreases in *Picea mariana*, DOC levels and lake productivity occurred between *ca.* 3500-3000 cal yBP, which has been attributed to treeline retreat (Moser & MacDonald 1990; Pienitz et al. 1999; Huang et al. 2004). The retreat coincided with decreasing summer insolation at high latitudes that decreased solar energy and temperature during the growing season at the treeline (Huang et al. 2004). High latitude

hemispheric cooling and circulation changes may explain the southward advance of the arctic front and the associated retreat of the treeline (Huang et al. 2004). Based on the Danny's Lake record, the effects of Neoglacial Cooling first began at 2600 cal yBP, roughly 400-900 years later than observed in more northerly sites, although sedimentation rates do drop at 3000 cal yBP to levels seen prior to the treeline migration (Crann et al. 2015).

At 1875 cal yBP we see a return of the coarser rEM-Overflow in the Danny's Lake record at unprecedented levels with several intervals exceeding 50% abundance. For the next 1300 years coarser rEM-Overflow intervals are common in the form of short sharp grain-size increases not sustained for longer than 2-3 subsamples. There is also a sharp increase in the sedimentation rate exceeding that of the early Holocene by 1700 cal yBP with a maximum sedimentation rate of 0.27 ± 0.04 mm/yr at 1300 cal yBP (Crann et al. 2015). This supports the interpretation that deterioration of vegetation cover within the catchment increased the amount of sediment available for erosion into Danny's Lake.

The temporal resolution of the Carleton Lake record is coarser than that of the Danny's Lake record. Robust EM-Suspended is the most common component throughout the Carleton Lake record. Intervals of rEM-Overflow begin as early as 2264 cal yBP in the Carleton Lake record and are more the rule than the exception in the early record, often comprising the entirety of the subsample (Appendix C.1 - Illustration C.1.6). The earlier appearance of rEM-Overflow at Carleton Lake compared to Danny's Lake supports the interpretation that the Polar Front migrated south, thus affecting more northerly sites

prior to more southerly sites. It must be noted that there is quite often a large unmodeled residual variance associated with rEM-Overflow. These intervals are of greater amplitude and regularity between 2250-1600 cal yBP supporting our interpretation that during this time Neoglacial cooling resulted in degradation of vegetation in the catchment. The sedimentation rate for Carleton Lake is much higher than that seen in Danny's Lake. There are several spikes in the sedimentation rate centered at 2264, 2127, 1257, and 942 cal yBP, which exceed 1 mm/year (Crann et al. 2015).

Between 1600-700 cal yBP (AD 350-1250) the intervals of rEM-Overflow in Carleton Lake are of reduced amplitude and regularity. The Medieval Climate Anomaly (MCA) is recognized as warm period taking place between ca. AD 950-1250 with a tendency for La Niña-like conditions in the tropical Pacific (Mann et al. 2009). In their study of a second core from the Carleton Lake record Upiter et al. (2014) found that the MCA occurred *ca.* 1100 cal yBP. As seen in the Danny's Lake record climate amelioration is usually associated with an increase in the abundance of rEM-Suspended possibly owing to extended summers, vegetation cover limiting erosion, reduced snowpack, retreat of permafrost and greater infiltration. In the Danny's Lake core from 930-740 cal yBP (AD 1020-1210) there is an interval with sustained elevated rEM-Suspended values and the disappearance of the coarser rEM-Overflow. Palynological analysis indicates that this was a period of renewed warmth (Sulphur et al, in prep) with temperatures similar to those of the Holocene Thermal Optimum. However, in the Danny's Lake record the increase in rEM-Suspended does not return to the levels seen during the Holocene Thermal Optimum. Sedimentation rates are reduced from the previous millennia but still

elevated in respect to those seen during the Holocene Thermal Optimum, with an average of 0.16 ± 0.04 mm/yr.

In Carleton Lake between *ca.* 700 and 500 cal yBP (AD 1250-1450) the regularity of rEM-Overflow increases but it is less abundant. After *ca.* 416 cal yBP the record consists only of rEM-Suspended. Little change was seen in the vegetation composition, implying that modern conditions had been established (Moser & MacDonald 1990). In the Danny's Lake record there are three intervals of coarser rEM-Overflow that follow the MCA including a large sustained interval centered at *ca.* 640 cal yBP. The coarser rEM-Overflow disappears after *ca.* 510 cal yBP. The timing of the end of rEM-Overflow in Carleton Lake and the coarser rEM-Overflow in Carleton Lake seems to suggest that there was a regional change in their catchments, possibly associated with deepening of the lakes due to the increased precipitation associated with the Neoglacial. Due to the error involved in radiocarbon dating it is not possible to say whether one change lagged behind the other.

3.8.1.5 Modern Times (500-Present)

Post 400 cal yBP the Carleton Lake record is comprised entirely of rEM-Suspended while the Danny's Lake record is dominated by rEM-Overflow. The Danny's Lake record ends at *ca.* 240 cal yBP, while the Carleton Lake record continues onto present day with the caveat that after *ca.* 600 cal yBP the dates are interpolated using the surface as representing 2012. Without the results of a multi-year sedimentation monitoring study the following is rather speculative. The pattern seen by Danny's Lake is in good

accordance with our hydrologic model as the primary source of sediment is due to overflow conditions during spring melt with a minor component due to summertime precipitation (Spence & Woo 2008). The Carleton Lake sedimentary record according to our hydrologic model reflects only summer time precipitation. Danny's Lake and Carleton Lake have many physical characteristics in common (Appendix C.2 - Table C.2.1). The main difference between these two lakes is their geographical position, Carleton Lake being north of the modern treeline and Danny's Lake being south. This has implications for the physical characteristics of their catchments. The Danny's Lake catchment lies within discontinuous permafrost and has a denser vegetation cover. Discontinuous permafrost results in an increased infiltration of summertime precipitation thus limiting surface flow during the summer months. The denser vegetation cover permits a greater amount of snow to accumulate in the catchment, as it provides shelter against the wind. Carleton Lake lies within continuous permafrost and has lesser vegetation cover as is typical of tundra sites. During the summer months the active layer is thinner than the active layer present in the Danny's Lake catchment and thus allows less infiltration. Without vegetation to block the action of wind during the winter, less snow accumulates within the catchment providing less hydraulic energy during the spring. The Carleton Lake sedimentation rate reached its slowest rate during the last 300 cal yr of the record. We cannot attribute any changes within the Carleton Lake sedimentary record to the late 19th century to present warming trends. (Francus et al. 2002) found a clear coarsening during the 20th century, specifically during the AD 1870s, 1810s, 1750s and ~1700, which we do not see in this record.

3.8.2 Limitations of the Study

Although it is tempting to derive direct deterministic deductions from the sedimentary record caution should be taken. These systems, although simplified in the Arctic, are still complex. The interplay of temperature and moisture changes is controlled by seasonal and longer-term precipitation variability. Hydrology is further controlled by the presence and extent of permafrost within the catchment. Ideally all sedimentological studies should monitor coring sites for several years to tease out the sedimentary processes but this is not always possible. This study demonstrates that there is still value in studying sedimentary records in the absence of monitoring data.

3.9 Conclusions

EMMA of three independent datasets of lake grain-size distributions, including a modern training set and two sediment cores, detected two EMs present in all three datasets: a rEM interpreted as a low energy or offshore suspension load and a rEM EM interpreted to represent spring overflow deposits. The EMs were successful in tracking variability associated with the *ca.* 8200 cal yBP hemispheric cooling event, which was triggered by the rapid northward drainage of the super lake formed by glacial lakes Agassiz and Ojibway. They also tracked hydrologic changes associated with changes in vegetation cover as related to climate amelioration during the Holocene Climate Optimum and deterioration associated with the onset of the Neoglacial Cooling seen in this record at 2600 cal yBP.

4 Chapter: Autoecological Approaches to Resolve Subjective Taxonomic Divisions within Arcellacea

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4.2 Foreword

Chapter 4 is the previously published “Autoecological Approaches to Resolve Subjective Taxonomic Divisions within Arcellacea” (Macumber et al. 2014). Arcellacea (Arcellinida, testate lobose amoebae) have previously been used to successfully track paleoenvironments and infer paleoclimatic conditions (Boudreau et al. 2005; Collins et al. 1990; Dallimore et al. 2000; McCarthy et al. 1995). This is no doubt a result of their sensitivity to varying hydroecological conditions (Kumar & Patterson 2000; Patterson et al. 1996; Reinhardt et al. 1998; Patterson et al. 2013; Neville, Christie, et al. 2010; Neville et al. 2011; Patterson & Kumar 2002; Roe et al. 2010). As discussed above the ultimate aim of the thesis was to evaluate and develop Arcellinida found in the treeline region as proxies for climate variability. Arcellinida can display ecophenotypic responses to changing conditions this makes them a valuable tool for building more complete paleoenvironmental reconstructions. Arcellinida also display a wide variety of phenotypic variability, which might not be due to autoecological pressures. A pragmatic approach was developed and presented to evaluate the validity of ecophenotypes in Arcellinida. This will aid in the discrimination between test morphologies that signify different environmental conditions.

The document has been reformatted to fit within the Carleton University Thesis Template. Illustrations and tables have been moved into separate appendices and references to them have been updated accordingly. Tim Patterson and Helen Roe were responsible for data collection. Tim Patterson was responsible for enumeration of the Arcellinida. Tim Patterson and Eduard Reinhardt originally came up with the study

concept. I was responsible for implementation of the study, which resulted in changes in the project design from the original plan. I drafted the manuscript. I undertook all statistics included in the manuscript. Graeme Swindles provided the idea for using PVclust and taught me how to implement it. All co-authors added feedback and revised the manuscript. The manuscript should be cited as follows:

Macumber, A.L., Patterson, R.T., Roe, H.M., Reinhardt, E.G., Neville, L.A., and Swindles, G.T., 2014. Autoecological approaches to resolve subjective taxonomic divisions within Arcellacea. *Protist* 165:305-316.

4.3 Abstract

Arcellinida (testate lobose amoebae) are important lacustrine environmental indicators that have been used in paleoclimatic reconstructions, assessing the effectiveness of mine tailings pond reclamation projects and for studying the effects of land use change in rural, industrial and urban settings. Recognition of ecophenotypically significant infra-specific ‘strains’ within Arcellinida assemblages has the potential to enhance the utility of the group in characterizing contemporary and paleoenvironments. We present a novel approach which employs statistical tools to investigate the environmental and taxonomic significance of proposed strains. We test this approach on two identified strains: *Diffflugia protaeiformis* Lamarck strain ‘acuminata’ (DPA), characterized by fine grained agglutination, and *Diffflugia protaeiformis* Lamarck strain ‘claviformis’ (DPC), characterized by coarse grained agglutination. Redundancy analysis indicated that both organisms are associated with similar environmental variables. No relationship was

observed between substrate particle size and abundance of DPC, indicating that DPC has a size preference for xenosomes during test construction. Thus DPC should not be designated as a distinct strain but rather form a species complex with DPA. This study elucidates the need to justify the designation of strains based on their autecology in addition to morphological stability.

4.4 Introduction

Arcellacea Ehrenberg, 1832 (Arcellinida) are rhizopods that construct a unilocular test. Also informally known as thecamoebians (Patterson & Kumar 2002) or testate lobose amoebae (Mitchell et al. 2008) they are characterized by lobose pseudopods, which protrude from the test aperture, and perform the dual functions of facilitating motility and feeding. They form small tests (5-500 μm) comprised primarily of agglutinated material (e.g. mineral grains and diatom frustules with autogenous cement). These tests preserve very well, and in great abundance (500-3000 specimens per ml) (Patterson & Kumar 2002). Arcellinida are important paleolimnological indicators, particularly in the lower pH conditions that typically characterize organic rich sediments (Medioli and Scott 1988; Patterson and Kumar 2002; Wall et al. 2009). Arcellinida assemblage data have been used to develop paleoclimatic reconstructions (Boudreau et al. 2005; Collins et al. 1990; Dallimore et al. 2000; McCarthy et al. 1995), to investigate mine-impacted lake sediments (Kumar and Patterson 2000; Patterson et al. 1996; Patterson et al. 2013; Reinhardt et al. 1998), to assess the effectiveness of mine tailings pond reclamation (Neville et al. 2010a; 2011) and to study the effects of urban development on lakes (Patterson et al. 2002; Patterson et al. 2012; Roe et al. 2010).

Traditionally a ‘morphospecies’ approach (i.e. species are distinguished based solely on morphologic traits) has been adopted to delineate Arcellinida taxa since sexual reproduction is thought to be rare or completely absent and the protoplasm decays rapidly precluding preservation (Charman 1999; Medioli and Scott 1983). Of late the “chastity” of testate lobose amoebae has come into question and it appears sexual reproduction is more common than previously thought (Lahr et al. 2011). The few molecular studies on living Arcellinida confirm that general test shape is a reliable taxonomic indicator (Gomaa et al. 2012). Matters are complicated though as several Arcellinida taxa are characterized by considerable morphologic variability. This has in the past resulted in taxonomic confusion (Medioli and Scott 1983; Medioli et al. 1987) revolving principally around the inability to properly quantify the degree of acceptable infra-specific variation (Charman 1999; Mazei & Warren 2012). Infra-specific variation refers to variation in morphology that is not significant enough to elevate a phenotype to the species level (Wanner 1999; Charman 1999), and is assumed to reflect ecophenotypic variation related to variable environmental conditions (Asioli et al. 1996; Patterson et al. 2002; Reinhardt et al. 1998; Wanner 1999). Smith et al. (2007) proposed that the within-species ‘lumping’ may be more genetically valid than ‘splitting’ as Arcellinida are characterised by phenotypic plasticity. Mazei and Warren (2012) recommended that taxa which are morphologically difficult to distinguish be lumped together into species “complexes”, but cautioned that information pertaining to environmental variability could be lost. In order to circumvent these issues phenotypes showing stable morphologies at the infra-specific level are designated as ‘strains’ (Asioli et al. 1996; Reinhardt et al. 1998). Strains are not

valid taxonomic divisions under the International Code of Zoological Nomenclature (ICZN), but their use increases the utility of using Arcellinida as environmental indicators (Asioli et al. 1996; Neville et al. 2010b; Patterson and Kumar 2002; Reinhardt et al. 1998). Laboratory experiments involving multigenerational morphologic analysis of Arcellinida clones under differing environmental conditions has confirmed that ecophenotypic variants exist (Medioli et al. 1987), and that in many cases these changes are controlled by environmental variables (Wanner 1999), as first proposed by Wallich (1864). For example, Asioli et al. (1996) demonstrated that Arcellinida living within contaminated lacustrine sediments in northern Italy responded to this environmental stress by displaying infra-specific variability.

The criteria for the designation of strains are based on a phenetic framework, where designations are based on the overall similarity of all observable traits (Medioli & Scott 1983). Although Asioli et al. (1996) employed several observable traits in their classification of strains including size, shape, processes and collar, the associated environmental conditions, which are assumed to solicit strain response, were not included. Advances in the ability to record environmental conditions in lakes and the development of new statistical approaches (e.g. canonical ordination), have led to significant improvements in the understanding of the association of various Arcellinida taxa with particular sets of environmental conditions (cf. Legendre and Birks 2012a). Thus it is possible for strain designations to not only include a morphological description but can also include a description of the associated environmental conditions controlling

expression of the observed infra-specific variation. This would enhance their ability to provide useful ecological information.

This study utilizes a distributional analysis of two long-recognized (Reinhardt et al. 1998) strains of *Diffugia protaeiformis* Lamarck strain ‘acuminata’ (DPA) and ‘claviformis’ (DPC), to demonstrate the applicability of statistical approaches to assess morphologic variants.

Both DPA and DPC produce xenogenous tests (Medioli & Scott 1988), but the distinguishing feature between them is the size of grains used to construct their tests (Reinhardt et al. 1998; Kumar & Dalby 1998). DPC uses coarse silt size grains, giving the test a rough outline (Appendix D.1 - Illustration D.1.5) and making it opaque under transmitted light. In contrast, DPA uses medium and fine silt size grains, giving the test a smooth outline (Appendix D.1 - Illustration D.1.5) and making it translucent under transmitted light (Patterson and Kumar 2002; Reinhardt et al. 1998). These two morphologic variants have previously been designated as strains on the assumption that selection of grain size in test construction, although distinct, was an infra-specific trait (Reinhardt et al. 1998). Possible correlation between available grain size in the environment and the distribution of DPC was never tested. The purpose of this research is to determine whether the observed variation between DPA and DPC is an ecophenotypic variation, an expression of substrate bias, or whether the variation reflects a preference, on the part of DPC, for coarser grains in test construction. The research was carried out using the distribution of Arcellinida as previously documented in a set of lakes that

spanned a variety of urban agricultural and forested settings in southern Ontario (Patterson et al. 2012; Roe et al. 2010).

4.5 Methods

The data set comprises 42 sediment-water interface samples collected from lakes and ponds in the Greater Toronto Area (GTA), Algonquin Park to the north and adjacent areas in eastern Ontario, Canada (Appendix D.1 - Illustration D.1.2). The Arcellinida species and strains, associated environmental properties of each station and methodologies employed were previously documented in Roe et al. (2010) and Patterson et al. (2012). Samples for this study were carefully selected to represent diverse limnological environments and contain statistically significant populations of DPA and/or DPC (after Patterson and Fishbein 1989; Boudreau et al. 2005). These samples in total contain 27 Arcellinida species and strains present in statistically significant populations. The Arcellinida faunal diversity within each sample was assessed using the Shannon Diversity Index (SDI), (Shannon 1948), which has been found to provide an indication of the relative health of lakes and ponds (Patterson & Kumar 2000; Roe & Patterson 2006). Q- and R-mode cluster analysis was carried out to identify Arcellinida assemblages (after Fishbein and Patterson 1993). Results were organized into a two-way cluster diagram (Appendix D.1 - Illustration D.1.2) using the PC-ORD (Version 6 for Windows) software package. PVCLUST (Suzuki & Shimodaira 2006) was used to calculate probability values for each cluster using multiscale bootstrap resampling techniques. Ordination analysis was carried out using CANOCO version 4.5 and CANODRAW (ter Braak 2002; ter Braak & Smilauer 2002). Detrended Correspondence Analysis (DCA) was used to

explore the inter-site characteristics of Arcellinida communities, and defined the gradient lengths characterizing the dataset. Datasets having gradient lengths < 2 SD indicated a linear response, while those with gradient lengths > 2 SD denoted a unimodal response (Birks 1995). DCA results indicated that our dataset had a unimodal response (2.73 SD). Subsequently Pearson product-moment correlation coefficient analysis was carried out to determine the intercorrelations between environmental variables and to provide an assessment of the degree of redundancy in the dataset (Birks 1995). Redundancy Analysis (RDA) was carried out to determine the relationships between Arcellinida taxa, sample sites and environmental variables (ter Braak 2002; ter Braak & Smilauer 2002). In these canonical ordination-type analyses, the data are constrained to correspond to a portion of the variation reported in a table of response variables (e.g. Arcellinida percent abundance) that is maximally related to a set of explanatory variables (e.g. measured environmental parameters) (Legendre & Birks 2012b). As a successful RDA analysis requires datasets to have a linear response our unimodal dataset was transformed using the Hellinger transformation (Legendre & Gallagher 2001). As per the work of Medioli et al. (1987) it is assumed that the abundance of DPC should parallel the abundance of coarser grains in the substrate. This assumption was tested by plotting the normalized percent abundance data was plotted on a ternary diagram representing the grain-size composition of the sites (Appendix D.1 - Illustration D.1.4) (Tri-plot Version 1.4; Graham and Midgley 2000). Percent abundance data was normalized to facilitate the groupings on the ternary plot (Appendix D.1 - Illustration D.1.4). The size ranges plotted for each axis were based upon a survey of scanning electron microscope images taken of DPC and DPA. The survey revealed that a significant proportion of grains on the order of

20 to 40 microns are incorporated into the growth plan of DPC (Appendix D.1 - Illustration D.1.5). Plotted data points were organized into four series: “Barren Samples” (0% abundance); “Below Average” (less than -0.5 standard deviations); “Above Average” (greater than 1 standard deviation); and “Average” (between 1 and -0.5 standard deviations).

4.6 Results

Interpretation of the Q-mode cluster analysis (Appendix D.1 - Illustration D.1.2) resulted in recognition of four distinct Arcellinida assemblages: ‘Nutrient Loaded’ (NLA); ‘Nutrient Poor’ (NPA); ‘High Conductivity’ (HCA), and; ‘Low Conductivity’ (LCA). R-mode cluster analysis (Appendix D.1 - Illustration D.1.2) permitted recognition of seven Arcellinida species and strains that had a significant influence on assemblage composition: *Centropyxis aculeata* (Ehrenberg 1832) strain “aculeata”; *Centropyxis aculeata* (Ehrenberg 1832) strain “discoides”; *Cucurbitella tricuspis* Carter 1864; *Diffflugia corona* Wallich 1864; *Diffflugia oblonga* Ehrenberg 1832 strain “oblonga”; *Diffflugia oblonga* Ehrenberg 1832 strain “tenuis”; and DPA. DPA and DPC occur within separate branches of the R-mode cluster analysis, branching at the highest level (Appendix D.1 - Illustration D.1.2) with DPA found within the cluster that contains other significant Arcellinida species and strains. DPC characterized a distinct cluster along with two other strains of *Diffflugia protaeiformis*: strain ‘protaeiformis’ and strain ‘scalpellum’, as well as *Diffflugia oblonga* strain ‘lanceolata’ and *Centropyxis constricta* (Ehrenberg 1843) strain ‘spinosa’. Cluster analysis using multiscale bootstrap resampling (Suzuki & Shimodaira 2006) found these clusters to be statistically significant ($p < 0.05$).

The RDA results indicated that a compilation of the first (Eigenvalue = 0.253) and second (Eigenvalue = 0.139) axes explained 39.2% of the variance in the species data and 56.1% of the species-environment relationship, while the measured environmental variables together explained 38.1%. Monte-Carlo permutation tests indicated that the first and all canonical axes were significant at $P < 0.002$ [see Roe et al. (2010) and Patterson et al. (2012) for an in depth discussion of the Arcellinida assemblages used in this research]. The centroids of the DPA and DPC correlations both displayed an intermediate fit within the plot. They are associated with dissolved oxygen, pH, calcium, oxygen reducing potential, and conductivity. Calcium, conductivity and pH showed the strongest correlation with DPA and DPC in this area of the RDA. DPA and DPC plotted orthogonally with sedimentary phosphorus in this study. This indicates that neither variant is sensitive to phosphorus loading, in contrast to other Arcellinida species (Patterson et al. 2012; Roe et al. 2010).

A survey of scanning electron microscope images taken of DPC revealed that a significant proportion of grains on the order of 20 to 40 microns are incorporated into their growth plan (Appendix D.1 - Illustration D.1.5). The coarse axes of the ternary diagrams represent the abundance of this class of particles (Appendix D.1 - Illustration D.1.4). The spread of abundances along this axis are thus especially important. The cloud of samples fell within the 10-75% coarse particle size, 35-45% medium particle size and the 15-35% fine particle size (Appendix D.1 - Illustration D.1.4). Inspection of the ternary diagrams revealed that “Above Average” samples for DPC were found toward

the lower portion of the sample cloud, associated with substrates with lower abundances of coarse particles (Appendix D.1 - Illustration D.1.4). “Average” and “Barren” samples are found spread equally throughout the sample cloud. Scatterplots (Appendix D.1 - Illustration D.1.4b-d) of the abundance of DPC versus each of the axes show there to be no clear relationship. DPA is present in the majority (35 out of 42) of samples, while DPC was found in fewer (22 out of 42) (Appendix D.1 - Illustration D.1.4b-d). Most samples that contained DPC also contained DPA except for a few exceptions (3 out of 42) and in most cases DPA is in greater abundance except in a minority of samples where DPC is most abundant (3 out of 42).

4.7 Discussions

Environmental Response

Arcellinida strains have generally been defined based on morphologic traits that are stable within a given population (Asioli et al. 1996; Patterson and Kumar 2002; Reinhardt et al. 1998). These are assumed to represent infra-specific variation resulting from distinct environmental pressures (Asioli et al. 1996; Patterson and Kumar 2002; Reinhardt et al. 1998), and thus environmental parameters associated with a given strain could also be used in defining it. Reinhardt et al. (1998) employed R-mode cluster analysis to gauge the validity of strain classifications in Arcellinida populations from two small lakes impacted by mine tailings near Cobalt, Ontario. They concluded that in order for infra-specific phenotypes to be recognized as distinct strains, they needed to cluster apart, as different clusters were assumed to represent different ecological conditions. Reinhardt et al. (1998) found DPA and DPC to cluster distinctively and thus concluded

that they were distinct ecophenotypic strains. The cluster analysis results in this study are in agreement with those of Reinhardt (1998) and show DPA and DPC clustering distinctively (Appendix D.1 - Illustration D.1.2). In contrast, Patterson and Kumar (2000), in an analysis of Arcellinida populations along a pH gradient in James Lake, northern Ontario, found that DPA and DPC clustered very close to each other, suggesting that the strains, at least in that lake, shared a nearly identical autecology.

Although R-mode cluster analysis can be used to distinguish between different Arcellinida assemblages, which may reflect distinct environmental conditions, it does so indirectly. Caution must therefore be taken in interpreting the results of a R-mode cluster analysis since the analysis itself may produce partitions irrelevant to any real discontinuities in the data (Legendre and Birks 2012a). We employed PVCLUST (Suzuki & Shimodaira 2006) a multiscale bootstrap resampling cluster analysis technique that assigns significance values to branching points. The results from the PVCLUST analysis confirmed that the clusters were statistically significant suggested that these two morphotypes should be classified as distinct strains.

Legendre and Birks (2012b) suggested that clustering techniques to not be solely applied to assemblage data, but rather to use in conjunction with ordination techniques such as RDA. Ordination techniques, which measure environmental variability directly, are much more robust in assessing whether two or more phenotypes share similar autecologies (Legendre and Birks 2012a). The RDA results do not support an ecological distinction between DPA and DPC (Appendix D.1 - Illustration D.1.3). Both plot near to one

another, and thus are associated with similar environmental parameters. These results correlate well with other ordination analyses results, where DPC and DPA were observed to plot close together (Kihlman and Kauppila 2012; Neville et al. 2010; Patterson et al. 2012). It must be noted that the environmental parameters incorporated are only those that could be measured, thus important environmental variables that might influence the autecology of these organisms could be missing. Also subtle differences in their ecology could exist, and the RDA plot might not be sensitive enough to fully capture these subtleties.

Correlation with Substrate

As discussed above DPC was defined as a separate strain based on its incorporation of coarse silt in its growth plan (Reinhardt et al. 1998). Based on an analysis of the mode of test construction observed in *C. tricuspis*, Medioli et al. (1987) had reservations about this approach as they experimentally determined that *C. tricuspis* was opportunistic in selecting materials to build their tests. Their results predict that DPC would be preferentially found in environments with higher percentages of coarse silt. Our results show no such trend, as all abundance categories (i.e. Above Average, Average, Below Average, and Barren) are spread across the sedimentary gradient (Appendix D.1 - Illustration D.1.2 & Illustration D.1.4). The same observation can be made for the distribution of DPA. This result suggests that DPC selectively chooses coarse grains to incorporate into its growth plan, regardless of the actual abundance of coarse silt in the substrate. Although grain-size selectivity has not been widely studied in Arcellinida, it has been commonly seen in agglutinated foramifera (Bowser and Bernhard 1993; and

references therein). Bowser and Bernhard (1993) observed that *Astrammia rara* Rhumbler selected large grains ($>300\text{ }\mu\text{m}$) for test construction from surrounding sediment characterized by a higher percent weight of smaller grain sizes ($<300\text{ }\mu\text{m}$). This preferential grain selection was attributed to an evolutionary pressure to build stronger tests to reduce the amount of cement needed to fasten the grains. As the cement is produced in the cytoplasm (Bender & Hemleben 1988) and therefore autogenous in nature – any mechanism that will reduce the energy requirement (e.g. using larger grains) to produce cement may present an evolutionary advantage. The recognition that Arcellinida will not undergo nuclear division in the absence of appropriate agglutinating material suggests that similar genetic linkages exist in this group as well (Stump 1936). Thus it can be said that DPC displays a selective behaviour when choosing grains to incorporate into its test.

Molecular data is needed in order to justify the elevation of DPC from a subspecies classification to the species level. Gomaa et al. (2012) published the first molecular data concerning *Diffugia* and found that general shell shape was a reliable indicator. The same could not be said about the structure of the organic cement used in test agglutination. Whether the variation in the amount of cement used in test construction represents specific variation still needs to be elucidated. It is the opinion of the authors that DPC be no longer considered a strain. The inclusion of coarser grains during test construction is not an ecophenotypical response, but could represent genetic underpinnings. In lieu of molecular data to support the elevation to a species level, DPC

and DPA should be complexed together, after Mazei and Warren (2012), as they share similar morphologies and similar autoecologies.

Including a description of environmental parameters that are associated with the morphospecies along with a morphologic description is a pragmatic method that will increase our understanding of the ecophenotypic variability within Arcellinida. Cluster analysis, both R-mode and multi-scale bootstrap analysis, separates DPA and DPC into separate clusters. RDA analysis showed that the separation of these strains was not due to measured environmental variables. Scatterplots and ternary diagrams revealed there was no relationship between substrate particle size and abundance of DPC. The results indicate that DPC are most likely selecting certain grain sizes, regardless of substrate abundance or environmental conditions. Thus further work is needed to see if this behaviour reflects a genetic basis. In lieu of this information it is the opinion of the authors that DPC should be complexed with DPA. This study further elucidates the need to justify Arcellinida strains based on a distinct environmental response in addition to morphological stability.

4.8 Conclusion

Including a description of environmental parameters that are associated with the morphospecies along with a morphologic description is a pragmatic method that will increase our understanding of the ecophenotypic variability within Arcellinida. Cluster analysis, both R-mode and multi-scale bootstrap analysis, separates DPA and DPC into separate clusters. RDA analysis showed that the separation of these strains was not due to

measured environmental variables. Scatterplots and ternary diagrams revealed there was no relationship between substrate particle size and abundance of DPC. The results indicate that DPC are most likely selecting certain grain sizes, regardless of substrate abundance or environmental conditions. This study further elucidates the need to justify Arcellinida strains based on a distinct environmental response in addition to morphological stability.

Our aim was to build upon the existing knowledge provided by reconstructions using chironimids, diatoms, pollen and various stable isotopes. Arcellinida are a valuable addition as they are ubiquitous throughout the region and are sensitive to changing lake conditions. This study provides a pragmatic approach to identifying valid ecophenotypes that can be used to track historical environmental variability ultimately linked with climate change.

In the final chapter of the thesis we look back and summarize important findings and look forwards to avenues of future research.

4.9 Systematics

Subkingdom PROTOZOA

Phylum AMOEBOZOA Lhe 1913

Class LOBOSIA (Carpenter 1861)

Order ARCELLINIDA (Kent 1880)

Superfamily ARCELLACEA (Ehrenberg 1830)

Family DIFFLUGIDAE (Stein 1859)

Genus *Diffugia* Leclerc 1815

***Diffugia protaeiformis* Lamarck strain ‘acuminata’**

(Figure 5, A-D)

Diffugia acuminata EHRENBERG, 1830, p. 95.

Diffugia acuminata Ehrenberg EHRENBERG, 1838, pl. 9, fig. 3.

Diffugia acuminata Ehrenberg var. *inflata* PENARD, 1899, pl. 3, fig. 1.

Diffugia curvicaulis PENARD, 1899, pl. 3, figs. 2-5.

Diffugia acuminata Ehrenberg CASH AND HOPKINSON, 1909, p. 22, fig. 43, not fig. 42.

Diffugia acuminata Ehrenberg SCOTT AND MEDIOLI, 1983, p. 818, fig. 9d.

Diffugia protaeiformis Lamarck MEDIOLI AND SCOTT, 1983, pl. 1, figs. 19-20 (not pl. 1, figs 15-18).

Diffugia protaeiformis Lamarck strain ‘acuminata’ REINHARDT ET AL., 1998, pl. 2, fig. 5.

Diffugia protaeiformis Lamarck strain ‘acuminata’ ROE ET AL., 2010, p. 960, Fig. 2p.

Diffflugia protaeiformis Lamarck strain ‘acuminata’ PATTERSON ET AL., 2012, p. 39, Fig. 4.25.

Diffflugia acuminata Ehrenberg MAZEI AND WARREN, 2012, not fig. 7 or 8, fig. 9 all except f and g, fig. 10 all except a or f or g.

Description. Test free, elongate, almost cylindroconical, fundus acuminate, tapering to form blunt basal process; anterior portion truncated at a right angle to form apertural opening, neck absent; aperture encompasses entire to almost the entire width of the test, aperture circular, narrow without lip; wall agglutinated, test smooth almost hyaline (i.e. transparent).

Remarks. Distinguished from *Diffflugia protaeiformis* Lamarck strain ‘claviformis’ (DPC) by having a thinner wall, which appears transparent under a light microscope and by having a smooth outline. DPC is also much more coarsely agglutinated. *Diffflugia curvicaulis* Penard, 1899 is identical to *Diffflugia protaeiformis* Lamarck strain ‘acuminata’ (DPA) with the exception of a curved basal process. We do not consider this minor variation a specific trait and thus consider *D. curvicaulis* to be a junior synonym of DPA.

Diffflugia protaeiformis Lamarck strain 'claviformis'

(Figure 5, E-I)

Diffflugia protaeiformis Lamarck morph 'protaeiformis' ASIOLI ET AL., 1996, p. 255, pl. 2, figs.1a,1b.

Diffflugia protaeiformis Lamarck strain 'claviformis' REINHARDT ET AL., 1998, pl. 2, fig. 3.

Diffflugia protaeiformis Lamarck strain 'protaeiformis' DALLIMORE ET AL., 2000, fig. 11.1,2.

Diffflugia protaeiformis Lamarck HOLCOVÁ, 2008, pl. 2, fig. 26.

Diffflugia protaeiformis Lamarck LORENCOVÁ, 2009, Fig. 13 (M,N).

Diffflugia protaeiformis Lamarck strain 'claviformis' KIHLMAN AND KAUPPILA, 2012, Fig. 3.26.

Diffflugia protaeiformis Lamarck strain 'claviformis' PATTERSON ET AL., 2012, p. 39, Fig. 4.27.

Diffflugia acuminata Ehrenberg MAZEI AND WARREN, 2012, fig. 7, fig. 8, fig. 9 f and g, fig. 10 a, f, g.

Description. Test free, elongate, almost cylindroconical, fundus acuminate, tapering to form blunt spine, anterior portion truncated at a right angle to form apertural opening, neck absent; aperture encompasses entire to almost entire width of the test, aperture circular, narrow without lip; wall agglutinated, test rough in outline, formed of irregular and angular clasts of medium to coarse grained silt, opaque under a light microscope and small.

Remarks. *Diffflugia protaeiformis* Lamarck strain ‘claviformis’ (DPC) is distinguished from *D. protaeiformis* Lamarck strain ‘acuminata’ (DPA) in having a coarser test made up of medium to coarse-grained silt particles, and is opaque under a light microscope. The use of strain names to refer to morphologic variants within the Arcellinida first appeared in the literature in the 1990s (e.g. Asioli et al., 1996, Reinhardt et al., 1998) and was used to delineate ecophenotypic populations where there was uncertainty as to whether distinct species existed (Patterson and Kumar, 2002). DPC is distinct from *D. protaeiformis*, as specimens of the latter species are typically characterized by an elongate test with a globular posterior region, which tapers over a very short interval to form a long shaft. This shaft, comprising 2/3^{rds} of the test, does not taper and is truncated perpendicularly, having an aperture that spans the width the test. Reinhardt et al. (1998) based identification of their DPC on the *D. claviformis* (Penard) of Ogden and Hedley (1980, p. 118, pl. 52, figs A-D). The specimens illustrated by Ogden and Hedley (1980) are actually the same as specimens illustrated by Reinhart et al. (1998) as *Diffflugia oblonga* strain ‘spinosa’ (Pl. 2, figs. 11ab). Ogden and Hedley (1980) in turn attributed their *D. claviformis* (Penard) to *Diffflugia pyriformis* var. *claviformis* Penard 1899 (p. 25, pl. 2, figs 12-14). Penard illustrated two different species in these figures. Although Pl. 2, fig 12 is attributable to the current concept of *D. claviformis*, the specimens illustrated on pl. 2, figs. 13, 14 are more likely attributable to *Diffflugia scalpellum* Penard, 1899, described in the same volume.

**5 Chapter: Temporal changes in Arcellinida faunas from a Canadian
Subarctic lake track Holocene climate variability**

5.1 Abstract

If current warming trends continue, the treeline is likely to extend northward, as occurred earlier in the Holocene during the Holocene Climate Optimum (HCO), replacing areas now occupied by tundra with forests, resulting in a decrease in albedo. These ecological changes could generate positive feedback that may lead to additional warming. It is important to gain a full understanding of the associated environmental changes during this potential analogue climate interval in order to better inform policy planners and climate modelers as to how the region may respond to future climate variability. This can best be achieved by analyzing multiple proxies as individual proxy may have different response times and sensitivity to climatic variations, and may respond to different factors within the climate system. To this end we sought have evaluated the utility of Arcellinida (testate lobose amoebae) as an additional biotic proxy for this region. We worked at Carleton Lake, following up on a previous study of chironimids in this small polymictic lake located north of the present treeline in the central Northwest Territories, where it had been demonstrated that hydroecological changes took place within the lake during the HCO. The results of a constrained incremental sum of squares analysis (CONISS) of Arcellinida faunas in Carleton Lake led to the identification of three distinct ecological zones. Zone 1 spanned *ca.* 6600-2800 cal yBP with the Arcellinida fauna reflecting higher productivity conditions associated with the forestation of the Carleton Lake catchment during the HCO. Zone 2 spanned *ca.* 2800-140 cal yBP, and is characterized by an increase in the average test size of several Arcellinida taxa during the Neoglacial. Zone 3 spans *ca.* 140 cal yBP to present. The Arcellinida fauna through this interval is

similar to that observed during the onset of the HCO and characterized the recovery of the region from the Little Ice Age.

5.2 Foreword

Chapter 5 is a follow-up study of a core from Carleton Lake previously analyzed by Uppiter et al. (2014) where a large shift in the chironomid community was observed to have occurred *ca.* 4600-4000 cal yBP when taxa more closely associated with tundra lakes were replaced by taxa more common in boreal environments. Comparison of the Uppiter et al. (2014) results to a previous study indicated that the timing of forestation at Carleton Lake lagged behind that observed at nearby Queen's Lake by 1000 years (MacDonald et al. 1993). The discrepancy in timing was hypothesized to be due to chironomid assemblages being driven by ecological factors in addition to air temperatures. Analysis of the Arcellinida communities within the Carleton Lake core was carried out to better constrain the timing and rate of treeline movement around Carleton Lake. The work was also carried out to better assess the applicability of Arcellinida as paleoclimate indicators in the north, as the only previous study was carried out on Richards Island in the only other study to have used Arcellinida in the Arctic Archipelago (Dallimore et al. 2000). The results presented here show that the Carleton catchment became forested *ca.* 5500 cal yBP in line with previous studies from other sites. The usage of Arcellinida strains as informal infrasubspecific taxonomic units permitted for the tracking of the Neoglacial onset, as cooler temperatures led to prolonged test growth prior to reproduction leading to larger tests in two species during cold phases, *Diffflugia globulosa* and *Diffflugia glans*. The results also demonstrate that

there is a significant shift in the Arcellinida assemblage at *ca.* 140 cal yBP, supporting results from other studies of diatoms paleoecology (Rühland & Smol 2005) for the onset of recent warming at the conclusion of the Little Ice Age.

5.3 Introduction

5.3.1 The importance of paleoclimate reconstructions

The Canadian Subarctic of the central Northwest Territories (Appendix E.1 - Illustration E.1.1) has undergone considerable climate change during recent climate trends ($\sim 1.5\text{-}2.0$ °C/decade from 1966 -2003; ACIA 2005). If the trend continues, the treeline is likely to extend northward, as occurred earlier in the Holocene, replacing areas now occupied by tundra (MacDonald et al. 2009). This ecological shift would result in a decrease in albedo in newly forested areas, and could generate positive feedback that may lead to additional warming (MacDonald et al. 2009). A better understanding of Holocene climate variability would inform policy planners and climate modelers as to how the region may respond to future climate variability. Unfortunately, there are only a few widely spaced climate records in the region, with the best instrumental meteorological record being found far south in Yellowknife, and that record only covers the post-1950 period. The lack of basic regional meteorological data makes quantification of Holocene natural climate variability for the central Northwest Territories difficult (ACIA 2005), requiring the use of paleoclimatic reconstructions (Bradley 1999).

Aquatic systems are particularly sensitive to changes in climate. A warmer climate shortens the duration of winter ice cover resulting in numerous indirect climatic

consequences such as lengthening of the growing season, changes in water chemistry, increased nutrient cycling, and increased primary productivity (Rühland & Smol 2005; Paul et al. 2010; Rouse et al. 2008). In contrast, colder climates result longer winter ice cover, often leading to deterioration of vegetation surrounding the lake (Chapter 3), and decreased nutrient inputs. Extended periods of winter ice cover can also lead to winter die off of fish as oxygen levels decline due to the prolonged isolation of lake waters from atmospheric oxygen recharge (Shuter et al. 2012). The sensitivity of treeline lakes to climate variability can be attributed to their chemically dilute nature, and their position at a major ecotone boundary (Pienitz et al. 1999). Rühland, Pienitz, and Smol (2003) found that one of the main differences between tundra lakes and boreal lakes was the dilute nature of the water present in the tundra lakes, largely due to the higher productivity of boreal lakes as a direct result of warmer temperatures. This sensitivity is showcased by many broad-scale patterns of Holocene climate change as previously identified using proxy evidence from the study of lake sediment cores (MacDonald et al. 1993; Wolfe et al. 1996; Pienitz et al. 1999; MacDonald et al. 2009; Rühland & Smol 2005; Moser & MacDonald 1990; Huang et al. 2004; Paul et al. 2010; Upiter et al. 2014). Three main stages of landscape development have been identified. The first stage occurred between ~8500 cal yBP and 6300 cal yBP when birch dominated shrub tundra transitioned to spruce forest tundra following regional deglaciation (Huang et al. 2004). The second stage was marked by a rapid forest expansion to about 50 km north of the present day treeline, likely reflecting a northward movement of the polar front between ~6300 to 3000 cal yBP (Moser & MacDonald 1990; MacDonald et al. 1993; Huang et al. 2004). The final stage began with the onset of the Holocene Neoglacial when cooling at 3000 cal

yBP resulted in southward retreat of the treeline to its current position (Huang et al. 2004).

5.3.2 The Holocene Climate Optimum

To better understand current climate trends, researchers look to warm intervals in the Earth's past as possible analogues. Paleoclimatic reconstructions can provide an interpretation of the state of the Earth that existed in reality, putting the results of estimates based on numerical climate models into context (Lunt et al. 2013). One such interval is the Holocene Climate Optimum (HCO) (*ca.* 6000 to 3500 cal yBP) when the treeline migrated greater than 50 km north in response to warmer-than-present temperatures (Moser & MacDonald 1990; MacDonald et al. 1993; Pienitz et al. 1999).

Upiter et al. (2014), in an analysis of the same core used in this study, found that the greatest shift in the chironomid community in Carleton Lake occurred *ca.* 4600-4000 cal yBP when taxa associated with tundra lakes were replaced by taxa more common in boreal environments. They interpreted this interval as representative of the forestation of the catchment as the treeline migrated northward. MacDonald et al. (1993) in their study of nearby Queen's Lake interpreted this episode to have occurred earlier, between *ca.* 5600 and 4000 cal yBP. The discrepancy in the timing between the studies has been hypothesized to be due to chironomid assemblages being influenced by environmental factors other than air temperatures (Upiter et al. 2014). There is thus uncertainty as to the timing and the rate of treeline migration and retreat within the catchment of Carleton Lake. This study utilizes a novel microfauna, Arcellinida, to provide an independent

paleoclimate reconstruction to better constrain the timing and rate of treeline migration around Carleton Lake.

5.3.3 Arcellinida as climate indicators

Arcellacea Ehrenberg, 1832, also informally known as thecamoebians (Patterson & Kumar 2002) or testate lobose amoebae (Mitchell et al. 2008), are characterized by lobose pseudopods and the construction of a unilocular test, ranging in size from 5 to 500 μm , and often comprised of agglutinated material (e.g. mineral grains and/or diatom frustules with an autogenous cement). The great preservation potential of their tests, rapid reproductive turnover rates and high concentrations in lake sediments (500-3000 specimens per ml in temperate lakes; Patterson and Kumar 2002) make them a valuable environmental proxy. Arcellinida assemblages have previously been used to assess paleoenvironmental conditions related to various anthropogenic forcings (e.g. Patterson, Barker, and Burbridge 1996; Reinhardt et al. 1998; Kumar and Patterson 2000; Patterson and Kumar 2000; Patterson et al. 2002; Kauppila, Kihlman, and Mäkinen 2006; Lorencová 2009; Neville et al. 2010; Neville, McCarthy, and Mackinnon 2010; Roe, Patterson, and Swindles 2010; Neville et al. 2011; Kihlman and Kauppila 2012; Patterson, Roe, and Swindles 2012). Fewer studies have used Arcellinida to track Holocene climate dynamics (McCarthy et al. 1995; Asioli et al. 1996), with only one completed in the Canadian Arctic (Dallimore et al. 2000). Previous studies have linked the size of Arcellinida tests to the duration of the reproductive season (Collins et al. 1990; Dallimore et al. 2000; Asioli et al. 1996; Lorencová 2009), with smaller on average test sizes being associated with longer reproductive seasons and warmer conditions. In

particular, Penard (1902) described two distinct forms of *Diffflugia globulosa*, one varying between 135-155 μm and one varying between 50 to 70 μm . McCarthy et al. (1995) successfully tracked regional Holocene climate dynamics in Atlantic Canada using a study of Arcellinida assemblages from three lakes. They identified community shifts in response to deglaciation, the HCO and the onset of the Neoglacial. In their study on Richards Island, NT, Dallimore, Schröder-Adams, and Dallimore (2000) found that Arcellinida were only able to colonize the lake starting at *ca.* 3000 cal yBP. They identified horizons associated with environmental improvement at *ca.* 1700 and 300 cal yBP where population abundances increased. Neither study showed the distinctive assemblage shift as recognized from diatom records in response to a profound environmental change beginning post-18th century and continuing to the present time (Rühland and Smol 2005; references therein). This study is the continuation of the previous investigation begun by Upiter et al. (2014) into the paleoclimate history archived in Carleton Lake, this time investigating temporal changes in the community dynamics of Arcellinida.

5.4 Methods

5.4.1 Core collection & stratigraphy

This study is part of the NSERC Strategic Grant “Impact of Climate Change on the Long-Term Viability of the Strategically Important Tibbitt to Contwoyto Winter Road, Northwest Territories”. Its goal was to better understand Holocene climate variability in the central Northwest Territories (Galloway et al. 2010; Macumber et al. 2012). The study site and the core have been previously described by (Macumber et al. 2012; Upiter

et al. 2014), and details regarding lake selection, core collection, age-depth modeling (Appendix E.1 - Illustration E.1.3; Appendix E.2 - Table E.2.1) (Crann et al. 2015) and sub-sampling can be found therein.

Carleton Lake (64°15'26"N, 110°06'03"W; elevation 417 m asl) has a surface area of 0.31 km², a catchment size of 1.4 km² and is located 120 km north of the present day treeline (Appendix E.1 - Illustration E.1.1). Detailed bathymetry was made available courtesy of Tetra Tech EBA (Appendix E.1 - Illustration E.1.2). It is a small cold polymictic lake that is well mixed year round (Chapter 2). Carleton Lake occurs within an area of continuous permafrost but lies close to extensive discontinuous permafrost (Natural Resources Canada 2009).

5.4.2 Treatment of subsamples

Forty-three sediment subsamples each 2.5 cm³ in volume were wet sieved through a 297 µm mesh to remove coarse debris and then through a 37 µm mesh to remove the clay fraction. Samples were subdivided into six aliquots for quantitative analysis using a wet-splitter (after Scott and Hermelin, 1993). Arcellinida were enumerated using an Olympus SZH dissecting binocular microscope (7.5-64X magnification). Many resources were referenced for Arcellinida identification (e.g., Penard 1902; Cash and Hopkinson 1909; Ogden and Hedley 1980; Scott and Mediolli 1983; Kumar and Dalby 1998; Patterson, Roe, and Swindles 2012). Arcellinida phenotypes showing stable morphologies are designated as 'strains' in order to circumvent taxonomic issues associated with the prevalence of phenotypic plasticity (Macumber et al. 2014). Strains are not valid

taxonomic divisions under the International code of Zoological Nomenclature, but their use increases the utility of using Arcellinida as environmental indicators (Patterson & Kumar 2002).

5.4.3 Statistical treatment

Statistically significant stratigraphic assemblage zones were identified using constrained incremental sum of squares (CONISS) clustering compared against a broken stick model using the rioja package in R (Juggins 2015; Grimm 1987).

The probable error (pe) was calculated for each subsample using the following formula:

$$pe = 1.96 \left(\frac{S}{\sqrt{Xi}} \right)$$

where S is the standard deviation of the population count and Xi is the fractional abundance (Patterson & Fishbein 1989). A subsample count was deemed statistically insignificant if the probable error exceeded the total count for a subsample. Standard error (Sxi) was calculated for each subsample using the following equation:

$$Sxi = 1.96 \sqrt{\frac{F1(1 - F1)}{Ni}}$$

where $F1$ is the fractional abundance of species and Ni is the total number of counts. A species was considered to be present in insignificant number if the standard error exceeded the total counts for that species in all subsamples (Patterson & Fishbein 1989). The Shannon Diversity Index (SDI) was used to characterize the faunal diversity of the species found in each subsample and to provide a general indication of the relative health of the subsampled lake (Shannon 1948). The SDI is defined as:

$$S.I. = - \sum_{i=1}^S \left(\frac{X_i}{N_i} \right) \times \ln \left(\frac{X_i}{N_i} \right)$$

where X_i is the abundance of each taxon in a subsample, N_i is the total abundance of the subsample, and S is equal to the species richness of the subsample. Environments are considered to be stable if the SDI falls between 2.5 and 3.5, in transition between 1.5 and 2.5, and stressed between 0.1 and 1.5 (Patterson & Kumar 2000).

To determine temporal trends in Arcellinida community assemblages preserved in the Carleton Lake sediment core, multivariate analysis was conducted using the vegan package (Oksanen et al. 2013) in R (Team 2014). A detrended correspondence analysis (DCA) indicated a gradient length of 0.18, therefore a principal component analysis (PCA) was chosen to evaluate temporal trends in the Arcellinida assemblages (ter Braak & Smilauer 2002; Legendre & Birks 2012b). Compositional variables are not free to vary independently (Reimann et al. 2008). It is thus sometimes necessary to use data transformations to open the data and eliminate the effects of closure (Reimann et al. 2008). We compared the untransformed dataset (closed) and the transformed dataset (opened) to observe if there was a benefit to using this transformation (Reimann et al. 2008). In this case there was none so the closed dataset was used for subsequent analysis. A log transformation was used to address asymmetry (Legendre & Birks 2012b) and a Euclidean distance function was used by applying a chord transformation (Legendre & Birks 2012b). A broken stick model (Legendre & Birks 2012b) was used to constrain the number of significant axes.

5.5 Results

5.5.1 Age-depth modeling

Crann et al. (2015) developed the age-depth model adopted herein using the IntCal13 calibration curves of Reimer et al. (2013) as shown in Illustration E.1.3 (Appendix E.1). This work was an update of a previous age-depth model developed from Upiter et al. (2014) that was based on the IntCal09. The differences in the two models are negligible.

5.5.2 Stratigraphy & sedimentology

Details of core collection and stratigraphy can be found in (Upiter et al. 2014) and (Macumber et al. 2012).

5.5.3 Arcellinida

Thirty-seven Arcellinida taxa were observed in 43 sediment sub-samples analyzed from the sediment–water interface to a depth of 90 cm in the sediment core (Appendix E.1 - Illustration E.1.4; Appendix E.2 - Table E.2.2). Only 27 taxa were present in statistically significant numbers and were chosen for further analysis. Three statistically significant Arcellinida zones were identified based on comparison of the CONISS results to a broken stick model (Appendix E.1 – Illustration E.1.4).

The basal zone, Zone 1, spanned 90 to 50 cm (ca. 6600 - 2800 cal yBP) and was characterized by equal proportions of *Diffflugia oblonga* Ehrenberg 1832 strain “oblonga” (DiOO) ($\bar{X} = 12.9 \pm 5.4\%$), *Centropyxis aculeata* (Ehrenberg 1832) strain “discoides” (CeAD) ($\bar{X} = 11.8 \pm 5.0\%$), *C. constricta* (Ehrenberg 1843) strain “aerophila” (CeCA) ($\bar{X}$

= $11.5 \pm 6.8\%$) and *D. globulosa* (Dujardin 1837) Penard 1902 strain “parvus” (DiGP) ($\bar{X} = 10.3 \pm 5.8\%$). Several other species are only present in the basal zone: *D. protaeformis* Lamark 1816, *Lagenodifflugia vas* Leidy 1874, *Lesquereusia spiralis* (Ehrenberg 1840), *Cyclopyxis kahli* (Deflandre 1929) (CyK) and *D. oblonga* strain “spinosa”. Of interest is the restriction of CyK to only one interval that marks the end of this zone. Zone 1 contained the highest test concentrations ($\bar{X} = 913.9 \pm 441.01\%$) and Shannon diversity index values (SDI) ($\bar{X} = 2.2 \pm 0.3$).

Zone 2 (46.5 – 3.5 cm; ca. 2500 - 175 cal yBP) was dominated by *D. globulosa* strain “globulosa” (DiGO) ($\bar{X} = 30.3 \pm 5.2\%$). Accessory species include *D. acuminata* Ehrenberg 1838 strain “acuminata” (DiAC) ($\bar{X} = 8.3 \pm 2.6\%$) and *D. glans* Penard 1902 strain “glans” (DiGA) ($\bar{X} = 7.8 \pm 4.9\%$). This zone is marked by a decline in the total concentration of tests ($\bar{X} = 496.2 \pm 211.0\%$) and SDI values ($\bar{X} = 1.9 \pm 0.2$).

Zone 3 (3 - 0 cm; ca. 150 cal yBP to Present) continues to be dominated by DiGO ($\bar{X} = 33.7 \pm 3.9\%$). We see decreases in DiGA and the disappearance of several *diffflugids* as well as *Pontigulasia compressa* (Carter 1864) (PoC) that were present in both Zone 1 and Zone 2. This zone is marked by an increase in the concentration of tests ($\bar{X} = 780.3 \pm 89.9\%$), but with little change in the SDI values ($\bar{X} = 1.9 \pm 0.1$).

A broken stick model applied to the PCA results (PCA-A, not shown) identified two significant axes, which explained 50 % and 14% of the variance, respectively. The first principal component (PC1-A) was positively associated with DiOO, CeCA, CeAD and DiGP. It was negatively associated with DiGO. PC1-A yielded elevated values for Zone

1 followed by a gradual decline prior to and after the Zone 1 - Zone 2 break. Low values continued throughout zones 2 and 3 until the present. The second principal component (PC2-A) was positively correlated with CeCA and *D. elegans* Penard 1890 (DiE) and inversely correlated with *D. glans* strain “magnus” (DiGM) and PoC. PC2-A exhibited elevated loading scores throughout Zone 1 followed by a sharp drop at ca. 4000 cal yBP and then a sharp increase at ca. 3000 cal yBP. Values remained constant throughout the remaining record with a slight increase in Zone 3. The variance associated with DiGO was quite substantial suggesting the possibility that it was masking variance in other species. To test this possibility, a second PCA was run excluding DiGO.

A broken stick model applied to the second PCA results (PCA-B) identified four significant axes, which explained 25%, 19%, 15% and 10% of the species variance, respectively (Appendix E.2 - Table E.2.3 & E.2.4). The first axis (PC1-B) was positively correlated with DiGA and DiAC and inversely correlated with CeAD, DiGP, and PoC. PC1-B had the inverse pattern to PC1-A, described above. The second axis (PC2-B) was positively correlated with DiGA, DiGm, and PoC and inversely with CeAD and CeCA. PC2-B shows the inverse relationship to PC2-A, as described above. Based on these results it was decided that no information was lost in removing DiGO; in fact information was gained. Therefore PCA-B was rather than PCA-A. The third axis (PC3-B) was positively correlated with DiOO, CeCA, DiGA and *D. acuminata* strain “*aspericolea*” and inversely correlated with Unknown species 7 (Sp7) and DiAC. This axis shows rather stable values throughout the record apart from decreased values between ca. 1000-500 cal yBP. The fourth axis (PC4-B) was positively correlated with CeCA, DiGM, DiGP, DiE

and inversely correlated with DiOO and CeAD. The loadings of PC4-B gradually increase between *ca.* 5900 and 5000 cal yBP and then declines between *ca.* 3900 and 2800 cal yBP where the Zone 1 - Zone 2 boundary occurs. The Zone 1 – Zone 2 break is characterized by low PC4-B principal component values, which gradually increase upward through Zone 2 and Zone 3 except for a brief excursion to lower values at *ca.* 1000 cal yBP.

5.6 Discussion

5.6.1 The Holocene Climate Optimum

Zone 1 of the core spans the period from *ca.* 6650 to 2800 cal yBP and chronicles the waxing and waning of the HCO. The rising and falling pattern of PC4-B through Zone 1 elegantly tracks this phenomenon, as it mirrors similar patterns observed in Toronto Lake (MacDonald et al. 1993), Lake TK20, Queen’s Lake (Edwards et al. 1996; Pienitz et al. 1999) and Carleton Lake (Upiter et al. 2014) (Appendix E – Illustration E.1.5). PC4-B is positively associated with DiGP, DiE and CeCA. DiGP is the smaller size variant of *D. globulosa* and is known to be indicative of warmer lake water conditions and longer reproductive periods (Asioli et al. 1996; Dallimore et al. 2000; Collins et al. 1990). DiE has been shown to be tolerant of high conductivities and increases in pH (Kihlman & Kauppila 2012). It is also associated with high abundances of pennate diatoms (Patterson & Kumar 2000). CeCA has been shown to be resistant to high conductivities (Kihlman & Kauppila 2012) and is associated with boreal forest sites (Neville, Christie, et al. 2010). Roe et al. (2010) found that this species showed a relatively low tolerance to anthropogenic phosphorus loading in their study of lakes from the anthropogenic

influenced Oak Ridges Moraine region of Ontario, but this was likely not a factor in Carleton Lake. We interpret the pattern of PC4-B in Zone 1 to reflect the HCO forestation of the Carleton Lake catchment. This would have resulted in increased nutrients being washed in from the catchment affecting the conductivity of the water column. It took *ca.* 1000 years for fauna to climax in response to forestation of the catchment and *ca.* 1300 cal yr for the fauna to decline, in a step-like fashion, in response to treeline retreat. As observed in the Toronto Lake pollen record (MacDonald et al. 1993), the pattern observed in PC4-B shows two peaks. One centered at *ca.* 5000 cal yBP and the other centered at *ca.* 4000 cal yBP. In their chironomid study of Carleton Lake Upiter et al. (2014) only recognized a single peak that coincided with a peak in total organic carbon, which is centered closer to *ca.* 4250 cal yBP. We propose that forestation began at *ca.* 5500 cal yBP, as was seen in Toronto Lake, and that the proposed HCO interval of Upiter et al. (2014) is representative of the climax thermal phase of the HCO. This is a reasonable hypothesis as during this interval the highest abundances of CeCA are recorded, prior to a sharp collapse at *ca.* 4000 cal BP.

5.6.2 Holocene Neoglacial

The Arcellinida assemblage of Carleton Lake core underwent a major faunal shift at *ca.* 2800 cal yBP, shifting from an earlier assemblage dominated by DiGP to a later assemblage dominated by DiGO. The CONISS results show this shift as a major break between Zone 1 and Zone 2 (Appendix E.1 – Illustration E.1.4). PC1-B exhibits a pattern of gradually increasing loadings across this transition. The timing of this transition is coincident with the onset of the Holocene Neoglacial, when cooling at *ca.* 3000 cal yBP

resulted in the southward retreat of the treeline to its current position (Huang et al. 2004; Paul et al. 2010). A similar timing was noted in the Danny's Lake grain size record at *ca.* 2600 cal yBP (Chapter 3) and seen in Queen's Lake by a reduction in mean annual temperature (Edwards et al. 1996) and dissolved organic carbon content (Pienitz et al. 1999) (Appendix E.1 – Illustration E.1.5). DiGO is considered to be a cold climate indicator (Collins et al. 1990; Lorencová 2009; Asioli et al. 1996) and is replaced by DiOO when organic content increases (Lorencová 2009). The only difference in morphology between the two strains of *D. globulosa* is the size of their tests; with DiGO varying between 135-155 µm and DiGP varying between 50 to 70 µm. As expected based on previous research, the larger test of DiGO is associated with the cooler conditions of the Neoglacial. This boundary is also marked by the only appearance of the terrestrial Arcellinida CyK, indicative of increased in-wash from the catchment associated with a deterioration of the catchment vegetation in response to cooling. At the Zone 1 – Zone 2 boundary, PC2-B and PC4-B exhibit decreased loading scores relative to their values between *ca.* 4000 to 2800 cal yBP. PC2-B is positively correlated with DiGA and DiGM. *Diffflugia glans* was one of the only living species present in March at Mildred Lake in northeastern Alberta (Neville, McCarthy, et al. 2010) displaying its tolerance to cold temperatures. As with the strains of *D. globulosa* the only difference between the strains of *D. glans* are their size. The increases in DiGM reflect the cooling of the climate. That these species benefitted prior to DiGO reflects perhaps a more opportunistic nature.

5.6.3 Post-140 cal yBP

A CONISS of done separately of the interval spanning *ca.* 2800 cal yBP to present showed a significant break at *ca.* 140 cal yBP. This transition is characterized by the disappearance of several *diffflugids* and PoC, which were present in Zone 1 and Zone 2. Zone 3 is characterized by decreased values of PC1-B, PC2-B and *D. glans* strains. Both DiE and CeCA trend slightly toward increasing abundances in Zone 3. This trend is not seen in PC4-B with which they are associated. Many studies including the study of Slipper Lake by Rühland and Smol (2005; and references therein) found one of the most pronounced changes in diatom assemblages occurred during the past *ca.* 200 years as indicated by a shift to a higher percentage of planktic taxa. They linked this assemblage change to longer ice-free periods associated with an increase in temperature as the region recovered from the Little Ice Age. The trends observed in the relative abundance of DiE and CeCA could thus reflect a response to changes in diatom assemblages. *D. elegans* has been linked to changes in the abundance of pennate diatoms (Patterson & Kumar 2000; Reinhardt et al. 1998). A decreasing trend in PC2-B and an increase in PC4-B displays a similar pattern to that seen in Zone 1 during the treeline migration (Appendix E.1 – Illustration E.1.5). Although this correlation is intriguing, at this time it remains rather speculative.

5.7 Conclusions

The utility of Arcellinida assemblages for tracking Holocene climate variability during the Holocene is demonstrated. These results help to constrain the timing and rate of treeline movement at Carleton Lake and showcase the value of Arcellinida as climate proxies. Constrained incremental sum of squares (CONISS) analysis resulted in the

identification of three distinct Arcellinida ecological zones. Zone 1 spanned *ca.* 6600-2800 cal yBP and characterized the hydroecology of the lake during the HCO. Our results are in good agreement with previous literature showing forestation of the catchment beginning at roughly *ca.* 5500 cal yBP. It took *ca.* 1000 cal years for fauna to climax and *ca.* 1200 cal years for the fauna to decrease. Zone 2 spanned *ca.* 2800-140 cal yBP, which represents the Neoglacial. This interval was characterized by an increase in the average test size of several Arcellinida taxa (e.g., DiGO, DiGM), reflecting prolonged growth phases prior to reproduction in response to cooler temperatures. Zone 3 spanned *ca.* 140 cal yBP to present and characterized the recovery of the region from the Little Ice Age. Similar patterns are observed in Arcellinida assemblages as were observed during the onset of the Holocene Climate Optimum.

6 Chapter: Conclusions

A spatial survey utilizing water property and geochemical data collected from lakes along the route of the Tibbitt to Contwoyto Winter Road was successful in demonstrating that differences exist between the limnology of taiga and tundra lakes (Appendix A). This result supported the subsequent use of lake sediment cores to track Holocene treeline migration in order to constrain natural climate variability. A mm-interval subsampling strategy enabled by use of a custom-designed sledge microtome significantly increased the temporal resolution of the new reconstructions over previous studies in this region (Chapter 2). This allowed tracking of the rate of climate amelioration and subsequent deterioration associated with the Holocene Climate Optimum (HCO) and the onset of the Neoglacial, as well as providing evidence of the hemispheric cooling event at *ca.* 8200 cal yBP (Chapter 3). The coarsening trend seen during the *ca.* 8200 cal yBP cooling event demonstrated that possible reworking of sedimentary layers is not an issue that precludes the use of mm-interval sampling strategy (Chapter 3). The use of multivariate ecological statistics combined with results from the survey of modern lakes provided validation for the use of Arcellinida ecophenotypes as ecohydrological indicators, which further contributes to the utility of using these taxa to track Holocene environmental variability (Chapter 4). Chapter 5 provided evidence that Arcellinida do respond to climate variability as major assemblage changes were linked to known Holocene paleoclimate events. Three ecological transitions were seen in the Arcellinida communities over the past *ca.* 6600 cal yBP. Zone 1 spanned *ca.* 6600-2800 cal yBP and featured a higher productivity Arcellinida fauna that reflected the position of the lake south of the treeline during the HCO. Zone 2 spanned *ca.* 2800-140 cal yBP, which

represents the Neoglacial. This interval is characterized by an increase in the average test size of several Arcellinida taxa, indicative of a prolonged protist growth phase prior to reproduction, which tends to occur with these organisms under cooler temperature conditions. Zone 3 spans *ca.* 140 cal yBP to present. The Arcellinida fauna through this interval is similar to that observed during the onset of the HCO and characterized the recovery of the region from the Little Ice Age.

The outcome of the NSERC strategic grant “Impact of Climate Change on the Long-Term Viability of the Strategically Important Tibbitt to Contwoyto Winter Road, Northwest Territories” was successful in many regards. Results from this project highlight the ability of northern treeline lake sedimentary deposits to archive Holocene climate variability. This research demonstrated that the Holocene has not been a climatically stable period. The results based on the grain-size and Arcellinida analysis indicate that these proxies provide considerable promise for recognizing the environmental response to Subarctic climate variability, including variability during the HCO, which if warming trends continue might provide an analogue for present day trends. Changes in vegetation impact catchment hydrology, which in turn has tremendous impact on lake trophic status. Approaching an investigation of these changes armed with as many proxies as possible results in more robust and coherent paleoclimate reconstructions. There is still much more work to be done though. Based on the research presented here as well as follow-on studies the next few years will undoubtedly see a drastic increase in the knowledge of Holocene climate variability for the central Northwest Territories. This data will not only inform policy planners and modelers for

this region, but will aid all those who work within the Taiga biome, the largest terrestrial biome on the planet Earth.

6.1 Recommendations

A goal that remained unrealized in this research was development of an Arcellinida-based transfer function. Juggins (2013) has suggested that the utility of transfer functions has been overstated in many research studies due to the inherent statistical limitations. The primary issue that hindered their use in this research was that the number of sites in the training set was only marginally adequate across such a diverse environmental gradient. The sixty sites investigated did not provide enough sites to both design the transfer function and independently test its reliability. There were also issues with the compatibility of data collected during different field seasons. These compatibility issues included factors such as different analyses run on different media (e.g. water versus lake sediment). Although now beyond the scope of this research the matter has recently been addressed not only within the northern training set where additional data was collected, but also for a new training set developed further south centered on Yellowknife. Incorporation of the southern training set with the northern data provides an adequate number of sites to permit future development of an Arcellinida-based transfer function.

The use of freeze cores and the application of the sledge microtome allowed for the documentation of an unprecedented temporal resolution in analysis of the northern treeline sediment cores. However, potential errors associated with the age-depth models exist as the dates were derived from bulk radiocarbon dates. There is also a lack of

independent chronological markers. A recent meta-analysis of age-depth models design from the cores used in this program demonstrates good agreement amongst the sediment cores. If the identification of the 8200 cal yBP cooling event in the Danny's Lake core can be further validated this could act as an independent chronological marker to be added to Bayesian age-depth models.

Results from a multi-year monitoring program of sedimentation in northern treeline lakes would have greatly helped in associating different size fractions with seasonal weather events, such as the spring freshet. Potential future work could compare results from end-member mixing analysis of the lake survey and lake cores to ground truthing data derived from a monitoring program. Multi-year monitoring programs have already been undertaken in high Arctic lakes with great success (Francus et al. 2008; Cockburn & Lamoureux 2008a; Cockburn & Lamoureux 2008b). The major difference between those systems and the lakes in this study is scale. Both Carleton and Danny's Lake are small lakes without rivers bringing in large volumes of water. Thus the question remains on what mechanism is truly driving dispersion of sediment within these lakes. Sediment traps deployed at proximal and distal sites to the shore as well as at shallow and deep intervals in the water column would allow us to distinguish between overflow, interflow or underflow. This would also give us the ability to identify localized density flows due to sediment instability. Observations made of the catchment over the course of the spring freshet would allow us to identify the mechanisms by which meltwater moves sediment into the lake and see how this changes between cooler and warmer years.

Chapter 3 and 5 presented semi-quantitative descriptions of Holocene climate variability. Future work would focus on using time series analysis to look for oscillatory patterns within the end-member and Arcellinida profiles. Teleconnections and other natural processes often display a periodic pattern that may be reflected in similar patterns seen in a proxy record. Preliminary results from time series analysis of grain-size records has identified periodicities associated with Pacific teleconnections, including the El Niño Southern Oscillation and the Pacific Decadal Oscillation. Other periodicities have been associated with solar cycles, such as the Gleissberg Cycle. Wavelet analysis would add a temporal dimension, allowing characterization of the timing and persistence of periodic behavior throughout the Holocene. This type of research would benefit climate modelers in their attempts to design regional climate models.

The datasets used herein presented many issues for the chosen statistical methods. Over the course of the thesis much effort has been placed on using a valid statistical methodology. For example the majority of the variables are non-normal. Early on in the thesis research parametric dependency tests were used when non-parametric tests would more appropriately have been used. Other issues that have been addressed include; dealing with structural zeros, compositional data, dimensionality and employing exploratory statistical analysis. The results in chapter 3-5 reflect this progress.

Appendices

**Appendix A - Paleoclimatological Assessment of the Northwest Territories and
Implications for the Long-Term Viability of the Tibbitt to Contwoyto Winter Road,
Part II: March 2010 Field Season Results**

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A.1 The Report

Foreword

The publishing of the 2011 Open Report represented the official breaking ground for the NSERC Strategic Project. We see here a clear outline of the rationale for this project, the setting in place of many key methodologies, systems and strategies of reporting that are still very much in use to this day. The 2010 field season was integral to the success of the NSERC Strategic Project due to the collection of a record number of freeze cores, which have been the source of many key studies that have come from this grant (Crann et al. 2015; Upiter et al. 2014)

This chapter is primarily a results report of material collected during the 2010 field season. At this point we had not completed much in depth work on the cores, but Chapter 04 will showcase the results from two cores, Danny's Lake and Carleton Lake. This chapter does include a preliminary synthesis of trends we observed in lakes based on their geographic position. We drew many similarities from previous research such as the Rühland, Piesnitz, and Smol (2003) study. Cataloguing the cores also gave us our first insight into the heterogeneity that exists in the sedimentary environments between lakes and the difficulty that exists in trying to find general trends between different lakes (Crann et al. 2015). It has served as a valuable reference for planning future studies as it not only includes a visual catalogue of all the cores but also age-depth models from a selection of cores.

The structure of this chapter is very straight forward. The methods section and the results/discussion section mirror one another. We begin with a look at why sites were included in the study followed by how we characterized the sites. We follow this up by doing a preliminary synthesis of latitudinal trends that we see across the treeline. Finally we describe the cores collected and the age-models that we developed.

Abstract

We characterize water quality data, as well as present biological and chemical data from lake sediments in support of an NSERC Strategic Project mandated to investigate background climate variability over the past ca. 3500 years in the southern Northwest Territories (NT). Goals of the project “Paleoclimatological assessment of the central Northwest Territories: Implications for the long-term viability of the Tibbitt to Contwoyto Winter Ice Road” include providing data to increase the understanding of natural climate variability in the southern NT in general, and the Tibbitt to Contwoyto Winter Road (TCWR) in particular. A complete understanding of past climate systems is critical to predicting future climate variability and impacts on northern ecosystems.

Eighteen lakes were sampled during the March 2010 field season (Appendix A.6 – Table A.6.1). A total of thirteen freeze cores, sixty Glew cores, twenty sediment-water interface samples, twenty bottom and top water samples and twenty vertical lake profiles were collected. The eighteen lakes sampled are spread along a latitudinal transect that spans the length of the TCWR from Tibbitt Lake to Lac de Gras. Lake sediment cores are composed mainly of mud, although a few contain intervals of sand and gravel. Freeze

coring was performed with a custom designed coring device that captured sediments on two faces and was successful in capturing the unconsolidated sediment-water interface. Sediment cores were digitally imaged and sedimentologically described and a subset was X-Ray imaged. Limnological properties and chemical characterization of lake water will be used in concert with analyses of sediment-water interface samples to develop Arcellinida (testate lobose amoebae) and diatom-based transfer functions. These transfer functions will be used to reconstruct environmental variables over the past 3500 years and quantify the regional climate variability. This research represents the first analysis of fossil and modern assemblages of Arcellinida in the southern NT and is only the second investigation involving Arcellinida, after Dallimore, Schröder-Adams, and Dallimore (2000), to occur in the territory. Other microfossil techniques, such as palynology and microscopic charcoal analysis, will permit reconstruction of treeline movement and the response of fire regime to past climate change.

Introduction

Background

The diamond industry is an essential component of the economy of the NT and the TCWR is the sole infrastructure for the ground transportation of goods and services to and from mines and projects north of Yellowknife. Cold winter temperatures are critical to the viability of the road, as 87% of the TCWR's 600 km length is composed of frozen lakes. Changing ice stability, thickness, and duration of ice cover associated with recent climate variability has dramatically impacted the use of the road. For example, an unusually mild and stormy winter in 2006 associated with the El Niño/Southern

Oscillation (ENSO) resulted in a substantially shortened road operation (26 days below average) and significant financial losses for industry. High costs for alternative transportation, such as air, negatively influences the feasibility of new mining operations, so it is critical for policy makers, planners, land users, and mine developers to understand the potential impact of future climate variability on the TCWR.

The detrimental fiscal impact of the 2006 winter underscored the need for a more complete understanding of which climate phenomena impact the region and how the region responds to natural climate variability. Instrumental records are few in number and only began in the 1940s. Even so they show a strong correlation to the positive and negative phases of the Pacific Decadal Oscillation (PDO) (Pisaric, St-Onge, and Kokelj 2009), a phenomenon driven by sea surface temperatures of the Pacific Basin. Previous climate reconstructions in the NT have shown that the climate of the NT has changed substantially and rapidly in the past (Pienitz, John P Smol, and Lean 1997; Rühland, Piesnitz, and Smol 2003; Huang, MacDonald, and Cwynar 2004; Rühland and Smol 2005). Employing only vegetational histories, sediment-water interface samples or single indicators of past climate or environmental change, these studies provide only a low spatial and temporal resolution (i.e. centennial-scale) that is insufficient to analyze climate variability on decadal and multi-decadal time scales (i.e. PDO and ENSO). Exceptions include the recent work of MacDonald et al. (2009) at Lake S41 where a temporal resolution of 90 years (including dating error) was achieved and the comprehensive studies conducted at Queen's Lake (MacDonald et al. 1993; Wolfe et al. 1996; Pienitz, Smol, and Macdonald 1999) and Toronto Lake (Moser and MacDonald

1990; MacDonald et al. 1993; Pienitz, Smol, and Macdonald 1999). A more complete understanding of which climate phenomena impact this region and their presence through time can only be achieved utilizing a high temporal resolution climate reconstruction, which is completely lacking in this region of the world.

Lakes are abundant in the central NT and their sediments contain continuous archives of biological, chemical, and physical proxies of recent and past environmental conditions that can be linked to climate (Chen et al. 2004; Conroy et al. 2008; MacDonald et al. 2009). For example, Arcellinida are abundant in benthic lacustrine habitats and research on this group has shown that Arcellinina are excellent proxies for paleolimnological and paleoclimatic study because their populations respond rapidly to changes in trophic status, pH, temperature, contamination, nutrients, and oxygen levels that can in turn, be linked to climate (Patterson et al. 1985; McCarthy et al. 1995; Booth 2001; Neville et al. 2010; Roe, Patterson, and Swindles 2010) including at high latitudes in Canada (e.g. Kliza and Schroder-Adams 1999; Dallimore, Schröder-Adams, and Dallimore 2000). Extant Arcellinida community composition in sediment-water interface samples will be statistically correlated to measured environmental variables. A transfer function will apply the modern biological community-environment relationship to sub-fossil Arcellinida community compositions preserved in the freeze cores. This approach will permit the quantitative reconstruction of environmental variables associated with climate for at least the past 3500 years. Another proxy of interest, particle size, is thought to reflect the energy of the surrounding catchment (Sun et al. 2002; Chen et al. 2004; Conroy et al. 2008; Kirby et al. 2010). Increased winter precipitation results in larger

freshets, which is associated with an increase in the size of detrital grains being washed into the lake. The alternation between coarser and finer average particle sizes in the core samples records the oscillations of climate phenomena in the area. Using time series analysis the signals of various climate phenomena can be reconstructed. These signals can they be compared to known global climate phenomenon.

By combining a multiproxy approach and a high resolution analysis, decadal to multi-decadal climate phenomenon will be resolved in the sediment cores. Qualitative and quantitative environmental reconstructions of the past 3500 years will aid in our understanding of how this region has responded to natural climate variability. This is the type of knowledge that is required to assess the impact of future climate variability whether natural, anthropogenic, or a combination of the two.

Objectives

Physical and chemical properties of lake sediments and surface and lake bottom waters will be used to characterize the biological, physical, and chemical properties of lacustrine systems along the TCWR. These types of data characterize the limnology of the basin and can be used to develop quantitative transfer functions to link the distribution of biological organisms during winter months to seasonal changes in water chemistry, for example. The results of this analysis will be applied to sediment core archives to reconstruct paleoenvironments during the last 3500 yrs. By investigating these paleoenvironments a qualitative climate history of the NT can be elucidated, and utilizing time series analysis cyclicity of various climate phenomena can be recognized.

Understanding which climate phenomenon impact this region and their effects on the regional watershed, will provide a robust and comprehensive scientific basis to evaluate the viability of present and future projects. The objectives of the March 2010 field season were to collect freeze cores, Glew cores (Glew 1991), water samples, and water quality measurements from lakes north of the 2009 field season sites (Galloway et al. 2010) to complete the latitudinal transect along the TCWR.

Study Site

The 2010 sampling program continued the north-south transect started during the 2009 field season to include sites from below, at, and above treeline (Appendix A.4, Illustration A.4.1; Appendix A.3, Table A.3.1). The study region is located within the Taiga Shield Ecozone (Directorate 1986). West of Hudson Bay, this ecozone spans northern Manitoba and Saskatchewan, southern portions of Nunavut, and the south central area of the NT. The climate of the Taiga Shield Ecozone is subarctic and continental, and is characterized by short summers and long, cold winters. Annual precipitation is low (175-200 mm) and mean daily January temperatures range from -17.5oC to -27.5oC while the mean daily July temperatures range from 7.5oC to 17.5oC. Boreal forests make up most of the groundcover of this ecozone and are dominated by stands of black spruce (*Picea mariana* (Mill.) BSP.) and white spruce (*Picea glauca* (Moench) Voss), with tamarack (*Larix laricina* (Du Roi) K. Kock) and pine (*Pinus* L.). Deciduous trees, including birch (*Betula* L.), trembling aspen (*Populus tremuloides* Michx.), alder (*Alnus* Mill.), and willow (*Salix* L.), grow in moist habitats. Along the northern limits of the ecozone, the boreal tree line is reached and forest stands are open

and lichen woodlands merge into areas of shrub tundra. The tundra vegetation cover can be discontinuous on rocky substrates and is dominated by lichen-heath, mosses, sedges, grasses, and diverse herbs (MacDonald et al. 2009). Small shrubs, most typically *Betula glandulosa* (dwarf birch), *Salix* (willow), alder (*Alnus crispa*), and various ericoids are common (Pienitz, John P Smol, and Lean 1997; Huang, MacDonald, and Cwynar 2004; MacDonald et al. 2009). Peat bogs in low-lying areas are dominated by Cyperaceae and *Sphagnum* (Pienitz, John P Smol, and Lean 1997; Huang, MacDonald, and Cwynar 2004).

Methods

Site Characterization

Lake Selection

The overall size and inflow outflow parameters were used to select target sites. In the absence of detailed bathymetry, the anecdotes of the Tibbitt Contwoyto Winter Road Joint Venture (TCWRJV) maintenance camp staff were used to improve the selection set. In addition several lakes identified as “problem lakes” by the maintenance camp staff were examined. The features that define problem lakes include lakes that freeze late and thaw early, that develop large areas of weak ice, and those associated with the escape of large amounts of methane from the substrate. Lake 26-1, Lake 27-1 and Lake 33-1 were identified as ‘problem lakes’ by the TCWRJV and were incorporated into the study. Small lakes, ponds, and bogs located adjacent to the TCWR were not targeted for coring for two reasons: 1) the truck equipped with a rear-mounted auger of adequate width for

freeze coring was unable to leave the TCWR; and 2) there is specific interest in how climate change may impact lakes along the TCWR. Future field work will target those sites that lie adjacent to the TCWR in 2011.

Coring Location

Ideal coring sites were more than 3 meters from shore, less than 8 m deep and contained a muddy substrate of suitable thickness (Galloway et al. 2010). It was also important that coring locations had a water column greater than 2 meters as to avoid the disruption to lake sediment caused by ice freezing to the lake bottom. During the annual lake thaw, as the surface melts, the ice frozen to the bottom of the lake floats up, pulling up lake sediment with it, thus removing part of the lake history. A fish finder and sounding line were used to measure water depth and a ‘pilot’ Glew core was used to investigate substrate type and thickness. If all criteria were met, the lake was cored with the freeze corer. GPS coordinates in NAD 83 were recorded at all sampling locations.

Water Quality Characterization

Winter water quality characteristics (dissolved oxygen, temperature, and conductivity) were recorded at each core location using an YSI multi-meter probe (Appendix A.5). Measurements were taken per meter depth at deeper sites and half-meter depth at shallower sites. Surface water pH was measured with a hand held pH meter. All equipment was calibrated according to manufacturer’s instructions. Ambient weather conditions (cloudiness, air temperature) were recorded for each day. Lake bottom water was sampled using a Kemmerer sampler and surface water was sampled directly. See

Table A.3.2 (Appendix A.3) for sample treatment in field prior to analysis. Cations and dissolved metals were analyzed using both ICP-MS and ICP-ES, alkalinity was measured using an automatic titration method (PC-Titrate), and trace anions were measured using a DIONEX EG40 coupled with ion chromatography. Samples measured for dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) were run on an OI Analytical "TIC-TOC" Analyser Model 1030 (St-Jean 2003). Samples for inorganic nutrient molecule analysis (P, NH₃, N) were submitted to Caduceon Environmental Laboratories, Ottawa, Canada.

Surface Sediment Sampling

Lake sediment-water interface samples were collected using a Glew corer (Glew, Smol, and Last 2001). In most cases, a top, middle, and bottom sample were sub-sampled from the Glew corer using the extruding device (Glew, Smol, and Last 2001). Selection criteria for suitable Glew coring sites followed the selection process for freeze coring. Due to speed of collection with the Glew coring method, more lakes were sampled (Appendix A.6 - Table A.6.1). Triplicate cores were collected from each lake to provide enough material for multiple analyses. Each site was approximately 0.3 m apart. Lake sediment-water interface samples were analyzed for a suite of analysis (see Core Analysis for methodology): microfossils (Arcellinida, chironomids, diatoms, and pollen), microscopic charcoals, loss on ignition (% moisture, % organics, % carbonate), particle size analysis, biogenic silica, oxygen and carbon isotopes and magnetic susceptibility. Phosphorus was also examined using the Olsen's phosphorus (Olsen P) extraction method, which provides a measure of bio-available phosphorus (Zhou, Gibson, and Zhu

2001) and is a suitable extraction method for samples of neutral to alkaline pH.

Phosphorus concentrations were determined using phosphomolybdate colorimetric technique (Watanabe and Olsen 1965). Results will be used in conjunction with samples collected during summer 2009, summer 2011, and to develop both Arcellinida and diatom-based transfer functions (Ter Braak and Prentice 1988; Galloway et al. 2010).

Freeze Coring

Coring

Two freeze corers, a single-faced and a double-faced freeze corer, were employed to collect continuous successions of lake sediment. Freeze corers are ideally suited for the recovery of high quality sedimentary successions, especially the unconsolidated and water saturated sediment near the sediment-water interface that is difficult to recover undisturbed using the open-tube corers (Lotter et al. 1997; Glew, Smol, and Last 2001; Kulbe and Niederreiter jr 2003; Blass et al. 2007). A single faced freeze corer was used during the March 2009 field season as described by Galloway et al. (2010). A custom-designed double-faced freeze corer, consisting of a rectangular pyramid chamber with one face covered by a wood board and the other two faces bare metal was also employed in March 2010 (Appendix A.2 - Illustration A.2.1). The exposed metal faces are used to collect the sediment. Each face is fifteen centimeters in width and over 2 m in length. The freeze core methodology employed was identical to that described by Galloway et al. (2010). An aluminum tri-pod with telescopic legs in conjunction with a boat winch (fastened to a modified trailer hitch) was used to raise and lower the freeze corers (Appendix A.2 - Illustration A.2.1). The use of the telescopic legs allowed us to

completely raise the freeze corer above the surface of the ice, facilitating successful recovery of undisturbed sediment.

Removal of Sediment & Sediment Core Preparation

Sediment was mostly completely frozen upon removal from the lake. Nonetheless, we allowed an extra ~10 minutes of freezing prior to transport. Freeze cores with frozen sediment were wrapped in a tarp and brought back to the maintenance camp where sediment was removed in frozen slabs. Slabs were laid on plastic wrapped wooden planks, information was recorded on the planks, and the slabs were encased in plastic wrap and secured with duct tape. Cores were then placed in coolers with dry ice and shipped frozen to Carleton University, Ottawa, Ontario, for detailed analyses.

Freeze cores are named as follows: (Project & Year)-(Lake Number or Name). Lakes along the TCWR are numbered according to what land portage they follow. P (portage)-39-1; is the first lake after the 39th land portage. P34-2 is the second lake after the 34th land portage. Some lakes, such as Lac de Gras, are referred to by a proper name when it exists, but also have a lake number assigned to them. Glew cores and water samples were named as follows: (Lake Number or Name)-(Replicate Hole Number) (Top, Middle or Bottom). 39-1-2T represents a Glew core collected from Lake 39-1, from the second replicate hole, and collected from the top of the Glew core.

Sedimentological Description

Sediment cores were unwrapped in the laboratory for sedimentological description following procedures and nomenclature outlined in (Schnurrenberger, Russell, and Kelts

2003). The upper surface (1 mm or less) of the cores was allowed to come to a temperature of ~4°C; the remainder of the sediment core was kept frozen. Sediment colour and grain size were determined using Munsell colour charts. Digital photos were taken of the cores (Prokoph and Patterson 2004) using a Canon EOS Rebel T1i EOS 500D camera with a Canon EFS 18-55mm lens (Appendix A.6 – Illustrations A.5.01-A.5.27). The camera was set to automatic under indoor lighting. An 18% gray card, printed gray scale and a 2.5y Munsell Colour Card were used as standards. Cores were X-Rayed at the Merivale Medical Imaging Centre using a Philips 527593, Bucky Diagnost TH and Fuji FCR (Appendix A.6 – Illustrations A.5.01-27).

Core Analysis

Bulk sediment samples and plant remains (e.g., twigs) were submitted to the 14CHRONO Lab, Queen's University, Belfast, and Beta Analytic Inc., Florida, U.S.A. for AMS radiocarbon dating (Appendix A.7 – Table A.7.1). Age-depth relationships shown in Illustration A.7.1 (Appendix A.7) include more dates than are displayed in Table A.7.1 (Appendix A.7), since the age-depth relationships were updated after submission of this report. Those cores with a suitable age model were then selected to be sub-sampled at a mm-scale resolution using a freeze core microtome (Macumber et al. 2011).

Material was collected at various resolutions for a suite of analysis including: particle size analysis with a Beckman Coulter LS13 320 Laser Diffraction Analyser. Particle size variations reflect the variability in catchment energy as a result of changes in levels of

precipitation and inflow to the lake. Low frequency magnetic susceptibility has been shown to reflect erosional rates and switches in source provenance. Loss on ignition using a (muffle oven), gives results about the shifts in moisture content, total organic carbon, carbonate and sediment content in the soil. Shifts in these percentages reflect variability in lake productivity and increases in erosional rates. Oxygen and carbon isotope analysis can track variations in lake levels and overall productivity. Microfossil assemblages (Arcellinida, diatoms, chironomids) are being analyzed to quantitatively reconstruct the paleoclimate of the region. Pollen and microscopic charcoal are being used to reconstruct vegetation and fire regimes of the region. Tree-ring analysis (dendrochronology) will be used at low latitude sites along the TCWR to provide an annually resolved terrestrial climate record to which other proxies can be compared.

Results & Discussion

Site Characterization

Lake Selection & Coring Location

Sites sampled span from latitude N62°27.600 to latitude N64°25.794 and from longitude W109°59.921 to longitude W114°43.603. A recent forest fire (~1997) occurred in close proximity to Lake 34-2 (Danny's Lake). Charcoal that has been deposited within the lake can be used as a chrono-stratigraphic marker. A burn is evident on air photos north of this site and Lake 46-1. Lake 46-1 and Lake 47-1 (Portage Lake) are located at the treeline (near the Snap Lake Mine turnoff). Lake 47-1 is a multi-basin lake, but is isolated from Mackay and P46-1. Lake McKay is almost 100 km in length. A sediment core from this

lake was collected at the northern end within a sub-basin. Lake 53-1 (Gravel Pit Lake) is located next to an esker with large lenses of frozen ice near the Lac de Gras maintenance camp. Lake 54-2 (Echo Lake) contained clear water and is located next to the Lac de Gras maintenance camp.

Water Quality Characterization

Site Characterization - Twenty one water samples (surface water and bottom water) were retrieved from eighteen lakes (Appendix A.4 - Illustration A.4.1; Appendix A.6 - Table A.6.1). Water quality data was collected from all eighteen lakes (Appendix A.5 - Table A.5.1). Water from Lake 40-1 and Lac de Gras had a sulfur smell. Water was tea-coloured, possibly due to a high concentration of dissolved organic carbon or humic substances. Peaty fragments were also observed in the Glew cores collected from these sites. Lake 49-1 also contained tea-coloured water.

Physical Parameters – The eighteen study lakes were generally between 10 to 1000 hectares in size but some very large lakes (P48-1 & P55-1) were included (surface area ranged from 2.3 to 97600 ha; median = 49.9 ha) (Appendix A.6 - Table A.6.1). The lakes were also generally shallow (maximum depth ranged from 1 to 6.5 m; median = 3.5 m) (Appendix A.6 - Table A.6.1). There were no significant differences ($p < 0.05$; Appendix A.3 – Table A.3.3) and no pattern was seen lake surface area or water depth across the three ecozones (Appendix A.2 – Illustration A.2.2). Surface area was negatively correlated at the $p < 0.01$ level with silica (Appendix A.3 – Table A.3.4). Depth was negatively correlated at the $p < 0.01$ level with conductivity, and various dissolved

elements (Ba, Ca, K, Mg) and at the $p < 0.05$ level with dissolved organic/inorganic carbon (DOC, DIC) and various dissolved elements (As, B, Cl, Li) (Appendix A.3 – Table A.3.4). Temperature profiles revealed all lakes to be isothermal to inversely stratified (Appendix A.5 – Illustration A.5.1). Inverse stratification occurs in winter and is related to the maximum density of water being 4°C Celsius, resulting in a warmer water mass being overlain by a colder less dense surface waters. There were no significant differences ($p < 0.05$; Appendix A.3 - Table A.3.3), but a slight trend of decreasing bottom water temperatures as one moves north (Appendix A.2 – Illustration A.2.2). Dissolved oxygen profiles revealed most lakes to have homogenous oxygen levels, with a few exceptions (P30-1 and P34-2) (Appendix A.5 – Illustration A.5.1). Dissolved oxygen levels were significantly different ($p < 0.05$; Appendix A.3 - Table A.3.3) between the lakes within the Boreal Forest and the Arctic Tundra and there is a general trend of increasing dissolved oxygen levels as one moves north (Appendix A.2 – Illustration A.2.2), with a few exceptions (P26-1, P27-1, P28-1, P51-1). Dissolved oxygen is negatively correlated at the $p < 0.01$ level with alkalinity, conductivity, DOC, DIC, and various dissolved elements (Al, B, Ba, Ca, Ce, Fe, K, Mg, Mn, Na, Pr, Si, Zn) (Appendix A.2 – Table A.2.4).

pH (Appendix A.5 – Table A.5.1) – Lake pH values were significantly different ($p < 0.05$; Appendix A.3 - Table A.3.3) in the Sparse Trees ecozone from those found in the Boreal Forest and Arctic Tundra ecozones. pH was not significantly correlated with any other environmental parameters (Appendix A.2 – Table A.2.4). There is a trend of increasing pH values from South to North (Appendix A.2 – Illustration A.2.2) with some exceptions

(P27-1, P39-1, P46-1, P47-1). The pH range (6.3 to 7.4 with a median of 7.0) (Appendix A.5 – Table A.5.3) is smaller than that recorded by in previous studies (Rühland et al. 2003). Interestingly, a circumneutral pH (range = 6.75 – 7.68) was recorded in all ‘problem lakes’ (P26-1, P27-1, & P33-1).

Trends in conductivity, alkalinity, and DIC (Appendix A.5 – Table A.5.1) - Lake water conductivity measurements show dilute waters that vary from 8 $\mu\text{S cm}^{-1}$ to 93 $\mu\text{S cm}^{-1}$. Tundra lakes have a median conductivity of 12.75 $\mu\text{S cm}^{-1}$ (range = 8 to 64.2), lakes in the Sparse Trees zone have a median conductivity of 16.5 $\mu\text{S cm}^{-1}$ (range = 13.5 to 17.1), and lakes in the Boreal Forest zone have a median conductivity of 26.8 $\mu\text{S cm}^{-1}$ (range = 12.8 to 93). The highest conductivity measured was in lake P40-1 (median = 93 $\mu\text{S cm}^{-1}$). There were no significant differences ($p < 0.05$; Appendix A.3 - Table A.3.3) in conductivity levels between ecozones, although differences between the Boreal Forest and Sparse Trees ecozone did approach it ($p = 0.0567$). Conductivity shows positive correlations at the $p < 0.01$ level with alkalinity, DIC, DOC, and various dissolved elements (Al, As, B, Ba, Ca, Ce, Cl, Fe, K, Li, Mg, Mn, Na, Pr, Si, Zn). Rühland et al. (2003) found that conductivity was positively correlated with Ca, Mg, Na, K, Cl, DIC. We found a similar trend to that reported by Rühland et al. (2003), of increasing ionic concentrations from Arctic Tundra to Boreal forest lakes. Rühland et al. (2003) interpreted this as the result of more restricted groundwater flow in tundra lakes that restrict net yield of base cations. Soils are also poorly developed relative to sites in the Boreal forest. Decreasing ionic concentration with latitude is also reported in other limnological studies near the Canadian treeline (Pienitz, John P Smol, and Lean 1997;

Pienitz, John P. Smol, and Lean 1997; Ruhland and Smol 1998; Duff et al. 1999; Fallu and Pienitz 1999; Gregory-Eaves et al. 2000; Fallu, Allaire, and Pienitz 2002). Alkalinity values range from 2 to 72 ppm with a median of 9 ppm (Appendix A.5 – Table A.5.3). The difference in alkalinity values approach significance between the Boreal forest and Sparse Trees ecozones ($p=0.0549$) and the Arctic Tundra ecozones ($p=0.0544$) (Appendix A.3 - Table A.3.3). There is a slight trend for decreasing alkalinity values moving from south to north (Appendix A.2 – Illustration A.2.2), with some exceptions (P49-1, P51-1). Alkalinity is positively correlated at the $p<0.01$ level with conductivity, DIC, and various dissolved elements (B, Ba, Ca, Ce, Cl, K, Mg, Na, Pr, Si), at the $p<0.05$ level with Fe and Mn (Appendix A.2 – Table A.2.4). Alkalinity is negatively correlated with dissolved oxygen ($p<0.01$; Appendix A.2 – Table A.2.4). The strong correlation of conductivity and alkalinity can be interpreted as these lakes representing closed systems. DIC ranges from 2.4 to 49 ppm with a median of 7.8 ppm, with similar values seen in surface and bottom water samples (Appendix A.5 – Table A.5.3). DIC did not show significant difference in values across the three ecozones ($p<0.05$; Appendix A.3 - Table A.3.3). There appears to be homogeneity in values for DIC with a few exceptions (P34-2, P49, P51) (Appendix A.2 – Illustration A.2.2). DIC displays a negative correlation to depth and dissolved oxygen ($p<0.05$ & 0.01 , respectively), a positive correlation at the $p<0.01$ level with alkalinity, conductivity, DOC, and various dissolved elements (As, B, Ba, Ca, Ce, Fe, K, Li, Mg, Mn, Na, Pr, Si) and at the $p<0.05$ level with Al and Zn. Dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC) can be used to interpret the state of organics, respiration of organisms and the overall mixing within a

lake. This sub-set of lakes is generally well-mixed, with little to no respiration by organisms (Appendix A.2 – Illustration A.2.3).

Trends in DOC – DOC values range from 2.8 to 94.7 ppm and have a median of 7.4 ppm (Appendix A.5 – Table A.5.3), with surface and bottom water samples showing similar values. DOC did not show significant difference in values across the three ecozones ($p < 0.05$; Appendix A.3 - Table A.3.3), although Boreal Forest $\delta^{13}\text{C}$ DOC values are significantly different from Sparse Trees sites ($p < 0.05$; Appendix A.3 - Table A.3.3) and approach significance in their differences from Arctic Tundra sites ($p = 0.0755$). DOC displays a negative correlation to depth and dissolved oxygen ($p < 0.05$ & 0.01, respectively), a positive correlation at the $p < 0.01$ level with conductivity, DIC, and various dissolved elements (Al, As, B, Ba, Ca, Ce, Fe, K, Li, Mg, Mn, Na, Pb, Pr, Si) and at the $p < 0.05$ level with Cu and Zn. Dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC) can be used to interpret the state of organics, respiration of organisms and the overall mixing within a lake. There is an enrichment trend due to the biodegradation of organics (Appendix A.2 – Illustration A.2.4). There appears to be a slight trend for lower values in the Arctic Tundra sites (4.8 ppm; Appendix A.5 – Table A.5.3) versus the Boreal Forest sites (10.5 ppm; Appendix A.5 – Table A.5.3), with a few exceptions (P34-2, P49, P51) (Appendix A.2 – Illustration A.2.2). Rühland et al. (2003) found similar results and attributed this to drainage of catchments with coniferous leaf litter, and wetlands bringing in high amounts of allochthonous DOC. They also found a relationship between water colour and DOC values. In our study, Lake P40-1, P49-1, and P55-1 all contained dark tea-coloured water. P40-1 does show extremely elevated DOC

values compared to other study sites, while P49-1 shows only a slightly elevated value compared to other Arctic Tundra sites and P55-1 displays one of the lowest DOC values (Appendix A.2 – Illustration A.2.2). Two lakes with elevated DOC values P39-1 and P51-1 did not have tea-coloured water.

Trends in nutrients – Ammonia values ranged from 0.440 to 7.820 µg/g with a median of 3.595 µg/g (Appendix A.5 – Table A.5.3). There was a significant difference ($p < 0.05$; Appendix A.3 – Table A.3.3) between Boreal Forest sites and Arctic Tundra sites.

Ammonia is positively correlated with total kjeldahl nitrogen (TKN) ($p < 0.01$; Appendix A.2 – Table A.2.4). There is a clear trend (Appendix A.2 – Illustration A.2.5) for higher ammonia values in Boreal Forest sites (median 26.050 µg/g) and lower values in the Arctic Tundra sites (median 3.595 µg/g). TKN values ranged from 438 to 18800 µg/g with a median of 5595 µg/g. There was a significant difference ($p < 0.05$; Appendix A.3 - Table A.3.3) between Boreal Forest sites and Arctic Tundra sites. TKN is positively correlated with ammonia and total phosphorus (TP) ($p < 0.01$; Appendix A.2 – Table A.2.4). There is a clear trend (Appendix A.2 – Illustration A.2.5) for higher TKN values in Boreal Forest sites (median 15200 µg/g), lower values in the Sparse Trees sites (median 9475 µg/g), and lowest values in the Arctic Tundra sites (median 3025 µg/g). TP values ranged from 85.9 to 1890 µg/g with a median of 777.5 µg/g. There was a significant difference ($p < 0.05$; Appendix A.3 - Table A.3.3) between Boreal Forest sites and Arctic Tundra sites. TP is positively correlated with TKN ($p < 0.01$; Appendix A.2 – Table A.2.4). There is a clear trend (Appendix A.2 – Illustration A.2.5) for higher TP

values in Boreal Forest sites (median 1031.5 µg/g), lower values in the Sparse Trees sites (median 955 µg/g), and lowest values in the Arctic Tundra sites (median 633.5 µg/g).

All three nutrient parameters show clear trends (Appendix A.2 – Illustration A.2.5) of decreasing values from as one moves from south to north. Rühland et al. (2003) found similar results and thought that the higher nutrient values in the Boreal Forest sites was related to higher runoff, higher precipitation, dense vegetation, increased breakdown of terrestrial litter and a longer growing season in combination with warmer temperatures elevating primary productivity and intensifying nutrient circulation. While in the Arctic Tundra sites, shorter growing seasons, cooler conditions, restricted hydrological processes, continuous permafrost and diminished catchment-derived nutrients resulted in overall lower primary productivity (Rühland et al. 2003).

Trends in dissolved elements – Concentrations for most of the dissolved elements were within the ranges provided by the Canadian Council of Ministers of Environment (CCME 2008), except for Fe concentrations (CCME guideline is 0.3 ppm) in P39, P40 and P51 which showed elevated concentrations (range = 2.5 to 9.5 ppm) (Appendix A.5 – Table A.5.2). These elevated Fe concentrations could be reflective of reducing conditions within these lakes (Davison 1993). Reducing conditions are common in lakes which have low oxygen levels, are shallow, and have a substantial amount of organic matter that can be subjected to decomposition (Davison 1993). P39, P40 and P51 show reduced oxygen levels (Appendix A.5 – Table A.5.1), and are shallow (Appendix A.6 – Table A.6.1). Further analysis will need to be done to see if the sediments are high in organic matter,

and if these conditions are permanent or rather a function of the winter ice cover. F, B, Cl, Na, Pb, Si, U, Zn all showed significant differences in values between Boreal Forest sites and Sparse Trees sites (Appendix A.3 - Table A.3.3). Br, F, Cs, Cu, Ni, Zn all showed significant differences in values between Sparse Trees sites and Arctic Tundra sites (Appendix A.3 - Table A.3.3). F, B, Na, U all showed significant differences in values between Boreal Forest sites and Arctic Tundra sites (Appendix A.3 - Table A.3.3). Several dissolved elements displayed positive correlations amongst each other (Appendix A.2 – Table A.2.4). B, Fe, Mn, Na, Si, and U show trends from south to north of decreasing values (Appendix A.2 – Illustration A.2.5). Several lakes always display higher values in comparison to lakes found close by (P39-1, P40-1, P51-1) (Appendix A.2 – Illustration A.2.5).

Ordination (PCA) – Principal components analysis (PCA), a multivariate ordination technique, was used to interpret the major patterns of variation in the environmental data by examining the strengths of each variable in explaining the principal directions of variation for 18 of the 20 sites (duplicate sites from P49 and P53 were excluded since they showed similar values). Data was normalized using the natural log so that all environmental variables were comparable. PCA was carried out using the computer program CANOCO version 4.0 (Ter Braak and Smilauer 1998). Since we were primarily interested in determining the interrelationships among the chemical and physical variables across the vegetational gradient, we treated latitude as a passive variable. The large differences in surface area between lakes also required that it too be run passively.

The study lakes in Illustration A.2.7 (Appendix A.2) cluster into three separate groups. Boreal Forest sites cluster together in lower right quadrant. These lakes are generally high in organics, and have moderate dissolved element concentrations. Of note is the relatively high concentration of uranium within these sites. A second grouping of sites in the lower left quadrant includes mostly Arctic Tundra sites. These lakes have low to moderate levels of nutrients but very dilute waters (low dissolved elements). The grouping found in the top left quadrant represents the Arctic Tundra sites that have very low nutrient values and low to moderate levels of dissolved elements. Overall all sites can be said to be relatively dilute, except for a few exceptions. Lakes P40 and P51 show relatively elevated dissolved element concentrations.

Surface Sediment Sampling

Twenty sediment-water interface samples were retrieved from eighteen lakes using the top sample from a Glew core (Glew, Smol, and Last 2001) (Appendix A.2 – Illustration A.2.1; Appendix A.5 – Table A.5.1). All sediment-water interface samples were surveyed for Arcellinida, diatoms, pollen and ostracods. All microfossils were present in abundance. Although present in the sediment-water interface samples, sediment cores were barren of ostracods. It is likely that acidification of sediments during decomposition of organic material dissolved the calcitic shells of ostracods. In northern lakes with high organic content and high concentrations of humic acids, it is unlikely that ostracods will be preserved in sedimentary successions. These sediment-water interface samples will form part of a larger sampling training set (Summer 2009, Summer 2011, Winter 2012) that will form the basis of Arcellinida and diatom-based transfer functions.

Freeze Coring

Coring

Thirteen sediment cores from eighteen lakes were retrieved using the freeze corer, and the latitudinal transect along the TCWR was completed (Appendix A.4 – Illustration A.2.3; Appendix A.6 – Table A.6.1). The latitudinal transect along the TCWR crosses three biogeographical zones and study sites are grouped accordingly: Boreal Forest, Sparse, and Arctic Tundra. Sedimentary successions varying in length from 27.3 cm (P39-1) to 152.3 cm (P30-1) (median = 87.1 cm) were retrieved.

Sedimentological Description & Core Analysis

All core descriptions make reference to photos and X-Rays displayed in Appendix A.6 (Appendix A.6 – Table A.6.1 & Illustrations A.5.01–A.5.27). The lake sediment-water interface was successfully captured in all freeze cores. Where the lake sediment-water interface is not a flat line, the middle point between its highest and lowest occurrence is used as the zero mark when measuring total core depth for descriptive purposes only.

ROAD10-BRIDGE1 (Appendix A.6 – Table A.6.1; Illustration A.6.01-02) – A freeze core was collected from P26-1 using the two-face freeze corer. The sediment-water interface was successfully captured on both faces. Face 1 was 60.9 cm in length and face 2 was 64.8 cm in length. The top 1 cm contained oxidized organic debris in a light grey/brown matrix (10yr 2/2). A gradual colour change to brown (10yr 2/1) takes place around 30 cm. There is a sharp colour change at 35.7 cm to light grey fine gray clay at

(5y 3/2). X-Ray analysis reveals banding at the base of face 2 within the clay fraction. Face 2 captured a longer sequence of the clay interval than face 1. No sub-samples were sent for radiocarbon dating.

ROAD10-BRIDGE2 (Appendix A.6 – Table A.6.1; Illustration A.6.03-04) - A freeze core was collected from P26-1 using the one-face freeze corer. The sediment-water interface was successfully captured. The core is 98.6 cm in length. The core is massive, with a gradual change from darker brown mud (10yr 2/1) to light brown mud (10yr 3/3) over the top 45.1 cm. There is colour change to lighter brown mud (2.5y 4/3) at 64.6 cm. There is a sharp transition to light grey (5y 3/2), fine grain mud at 79.1 cm. X-Ray analysis reveals little internal structure but does show that there is a density change that corresponds with the visual colour change. No sub-samples were sent for radiocarbon dating.

Attempts by Dr. Graeme Swindles, Leeds University, UK, to isolate crypto-tephra in Road10-Bridge1 were unsuccessful. One cm sub-samples were analysed for the presence of cryptotephra following Turney (1998) and Swindles, Vleeschouwer, and Plunkett (2010). It appears that the Bridge River and White River ash plumes were not deposited in Bridge Lake, despite reports of the latter visible in peatlands west of Yellowknife (Robinson 2001).

ROAD10-PAT'S LAKE (Appendix A.6 – Table A.6.1; Illustration A.6.05-07) - A freeze core was collected from P30-1 using the one-face freeze corer. The sediment-water

interface was successfully captured, although it must be noted that the interface for this lake is extremely soupy. The extremely high water content of the surface sediments of this lake makes it difficult to discern a true sediment-water interface. The core is 152.3 cm in length. The core is massive and made up of dark brown organic mud (10yr 2/1). X-Ray analysis reveals no internal structure that cannot be explained by artifacts of the analysis or coring procedure. No sub-samples were sent for radiocarbon dating.

ROAD10-DANNY'S LAKE (Appendix A.6 – Table A.6.1; Illustration A.6.08-12) – A freeze core was collected from P34-2 using the two-face freeze corer. The sediment-water interface was successfully captured on both faces. Face 1 is 118 cm in length and face 2 is 116.2 cm in length. Both faces show similar colour changes and are made up of similar sediment. The faces are massive and made up of fine organic mud. The upper 70 cm are homogenous dark brown organic mud (10yr 2/2). The next 24.1 cm see several gradual colour changes from dark brown to a lighter brown/yellow (to 7.5yr 2.5/2 to 2.5y 3/2). A distinct colour change from (2.5y 3/2 to 2.5y 4/3) takes place at 93.9 cm in face one and at 90.6 in face two. An indistinct colour change takes place at the base from (2.5y 4/3 to 2.5y 2/1). X-Ray analysis reveals little internal structure but does show that there is a density change that corresponds with the distinct visual colour change. Thirteen bulk material sub-samples have been submitted for radiocarbon dating (Appendix A.7 - Table A.7.1). The age-model (Appendix A.7 - Illustration A.7.1) shows a roughly consistent sedimentation pattern over the last 8112 ^{14}C yr with one age reversal at the base of the core. The average sedimentation rate for this core is 0.01 cm/yr.

NOTE ON RADIOCARBON DATING FREEZE CORES IN NT - Chronological control is critical to establish sedimentation rates and estimating the temporal resolution of each sub-sample. Age-depth relationships of sediment cores were modeled using the Clam computer program (version 1.0.2; Blaauw 2010; Appendix A.7 - Illustration A.7.1). All radiocarbon ages were calibrated using the IntCal09 dataset (Reimer et al. 2009). An old carbon reservoir effect may occur in some of the lakes. We know the sediment-water interface to have been captured (visual determination), yet the radiocarbon-based age-depth models suggest that surface samples may be as much as 400 years old. Old-carbon may be derived from carbonates contained in glacially derived surficial geology in the central NT (Sutherland, 1980). An alternative hypothesis is that if ice froze to lake bottom, then recently accumulated sediments may be frequently disturbed. To address the discrepancy between our visual observations of sediment-water interface core capture and age-depth relationships based on radiocarbon, we are using ^{210}Pb dating, unaffected by reservoir effects, of upper sediments of cores.

ROAD10-39-1A (Appendix A.6 – Table A.6.1, Illustration A.6.13-14) – A freeze core was collected from P39-1 using the two-face freeze corer. The sediment-water interface was successfully captured on both faces. Face 1 is 27.3 cm in length and face 2 is 27.9 cm in length. Both faces are massive and made up of dark brown (2.5y 2.5/1) fine organic mud. X-Ray analysis reveals no internal structure that cannot be explained by artifacts of the analysis or coring procedure. Three bulk material sub-samples have been submitted for radiocarbon dating (Appendix A.7 - Table A.7.1). The age-model (Appendix A.7 - Illustration A.7.1) shows that the top of this core is abnormally old (3597 ^{14}C yr at 10

cm). P39-1 is a very shallow lake 1 to 1.25 m in depth. Thus if this lake freezes to bottom during the winter surface sediments could be rafted to the surface, explaining the age of the top of the core.

ROAD10-39-1B (Appendix A.6 – Table A.6.1, Illustration A.6.15) – A freeze core was collected from P39-1 using the one-face freeze corer. The sediment-water interface was successfully captured. The core is 29.3 cm in length. The core is massive and made up of dark brown (2.5y 2.5/1) fine organic mud. This core was not submitted for X-Ray analysis and no sub-samples were sent for radiocarbon analysis.

ROAD10-46-1 (Appendix A.6 – Table A.6.1, Illustration A.6.16-17) – A freeze core was collected from P46-1 using the two-face freeze corer. The sediment-water interface was successfully captured on both faces. Face 1 is 33.3 cm in length and face 2 is 36.9 cm in length. Both faces are massive, made up of fine organic mud, and show similar colour changes. The top 5 cm of the cores is made up of a dark grey/green algal mix (2.5y 5/2) followed by an indistinct colour change to (5y 4/1). The rest of the cores show a gradual change to a lighter grey. At 12 cm there is an indistinct colour change to (5y 3/2), at 17 cm an indistinct change to (5y 4/1), and finally at 23 cm an indistinct change to (2.5y 4/1). The X-Ray reveals a slumping texture in the middle of face 2. From the left side to right side, there is a gradual incline with a sharp drop to the right visible in several layers. This may be due to topographic differences or as an artifact due to the coring method. No sub-samples were sent for radiocarbon analysis.

ROAD10-47-1 (Appendix A.6 – Table A.6.1, Illustration A.6.18) – A freeze core was collected from P47-1 using the one-face freeze corer. The sediment-water interface was successfully captured. The core is 85.7 cm in length. The entire core is massive and made up of light brown (2.5y 3/2) fine organic mud. X-Ray analysis reveals no internal structure that cannot be explained by artifacts of the analysis or coring procedure. Four bulk material sub-samples have been submitted for radiocarbon dating (Appendix A.7 - Table A.7.1). The age-model (Appendix A.7 - Illustration A.7.1) shows that the top of this core is abnormally old (4218 ^{14}C yr at 13.5 cm). Unlike P39-1, P47-1 is not a very shallow lake at 4.85 m in depth (Appendix A.6 – Table A.6.1). It is a relative large lake (194.9 ha) compared to a lake like P34-2 (19.2 ha), and is also connected to an even larger lake P46-1 (1108.3). Thus the bottom sediments might be subjected to bottom currents that can develop through wind fetch in such large systems.

ROAD10-49-1A (Appendix A.6 – Table A.6.1, Illustration A.6.19) – A freeze core was collected from P49-1 using the two-face freeze corer. The sediment-water interface was successfully captured on both faces, but the interface on Face 1 shows a strong inclination. Face 1 is 70.8 cm in length and face 2 is 88.3 cm in length. Both faces are massive, made up of fine organic mud, and show similar colour changes. The majority of the faces is made up of brown mud (2.5y 3/2 and at the base of Face 2 there is a gradual colour change to a darker brown mud (2.5y 4/3). This core was not submitted for X-Ray analysis and no sub-samples were sent for radiocarbon analysis.

ROAD10-49-1B (Appendix A.6 – Table A.6.1, Illustration A.6.20-21) – A freeze core was collected from P49-1 using the one-face freeze corer. The sediment-water interface was successfully captured. The core is 111.2 cm in length. The entire core is massive and made up of light brown (2.5y 3/2) fine organic mud. There is a gradual transition from light to darker brown (2.5y 4/3) mud towards the base of the core. X-Ray analysis reveals no internal structure that cannot be explained by artifacts of the analysis or coring procedure. Three bulk material sub-samples have been submitted for radiocarbon dating (Appendix A.7 - Table A.7.1). The age-model (Appendix A.7 - Illustration A.7.1) shows a roughly consistent sedimentation pattern over the last 5663 14C yr. The average sedimentation rate for this core is 0.02 cm/yr.

ROAD10-52-1 (Appendix A.6 – Table A.6.1, Illustration A.6.22-24) – A freeze core was collected from P52-1 using the two-face freeze corer. The sediment-water interface was successfully captured on both faces. Face 1 is 101.6 cm in length and face 2 is 104.7 cm in length. Both faces are massive and made up of fine organic mud. The upper 53 cm are homogenous dark brown organic (10yr 3/3) mud. The next 23 cm see a gradual colour change from dark brown to a lighter brown (2.5y 4/3). An indistinct colour change from (2.5y 4/3 to 2.5y 5/2) takes place at 76 cm. X-Ray analysis of face two reveals no internal structure that cannot be explained by artifacts of the analysis or coring procedure. Seven bulk material sub-samples have been submitted for radiocarbon dating (Appendix A.7 - Table A.7.1). The age-model (Appendix A.7 - Illustration A.7.1) shows a roughly consistent sedimentation pattern over the last 8011 14C yr. The average sedimentation rate for this core is 0.01 cm/yr.

ROAD10-ECHO (Appendix A.6 – Table A.6.1, Illustration A.6.25) – A freeze core was collected from P54-2 using the two-face freeze corer. The sediment-water interface was successfully captured on both faces. Face 1 is 87.7 cm in length and face 2 is 86.5 cm in length. Both faces are massive, poorly sorted (mud-pebble), dark brown (2.5y 3/2) sediment. There is an indistinct transition from dark brown to light brown (10yr 3/3) towards the base of the core. This lake is located near an esker, a source of gravel for land portages, and is the likely source of gravel that may have been transported to the basin during periods of high runoff. This core was not submitted for X-Ray analysis and no sub-samples were sent for radiocarbon analysis.

ROAD10-LACDEGRAS (Appendix A.6 – Table A.6.1, Illustration A.6.26-27) – A freeze core was collected from P55-1 using the two-face freeze corer. The sediment-water interface was successfully captured on both faces, except face 1 shows a depression in the interface. Face 1 is 44.7 cm in length and face 2 is 49.2 cm in length. Face 1 appears to be distorted and could be due to the coring process. Face 2 shows several colour and stratigraphic changes. The upper 0.5 cm is composed of what appears to be oxidized orange/red (2.5yr 4/8) sediment. Several colour changes take place below this oxidized layer from a dark grey (2.5y 3/1) to: (2.5y 4/1) at 5 cm, (5y 5/1) at 8 cm, (2.5y 4/1) at 15.8 cm, (5y 4/1) at 17.4 cm, and (10yr 4/1) at 23 cm. Dark inclusions were noted at 17 and 21 cm. Small black specks are noted throughout the core. X-Ray analysis of face 1 confirms that the sedimentary layers have been distorted, while X-Ray analysis of face 2 shows that the sedimentary layers have been preserved. Of note is distinct

laminations at the base of the core. Three bulk material sub-samples have been submitted for radiocarbon dating (Appendix A.7 - Table A.7.1). The age-model (Appendix A.7 - Illustration A.7.1) is rather troublesome for this core, with an age reversal and a abnormally old age at the top of the core.

Conclusion

Eighteen lakes were investigated during the 2010 field season. Thirteen freeze cores, twenty sediment-water interface samples, and twenty-one surface and bottom water samples were collected. Water quality data and vertical temperature-dissolved depth profiles were generated for each study site. Water quality data shows similar trends to a previous study by Rühland et al. (2003). The latitudinal transect along the Tibbitt to Contwoyto Winter Road was successfully completed. We now have data collected from lakes that span from latitude N62°27.600 to latitude N64°25.794 and from longitude W109°59.921 to longitude W114°43.603 in the central NT.

Sedimentological description and X-Ray imaging demonstrate that the majority of sediment cores exhibit a massive sedimentological structure, consist of fine organic mud with both abrupt and gradual colour changes, and show little density variation. No varves or annual layering was observed. Age modelling of a subset of the freeze cores confirms that there are lakes that will be suitable for high resolution paleoclimatic reconstruction. Material collected during the 2010 field program will be used to meet the mandates of on-going research programs. Sediment-water interface samples will be combined with

samples collected during August 2011 and during future field expeditions and from the basis of both Arcellinida and diatom based transfer functions.

A.2 Illustrations

Illustration A.2.1. Deployment of tri-pod suspending double faced freeze corer during freeze coring on lake P47-1 (March 10th, 2010; TCWR, NT).

Illustration A.2.2 – Trends in selected variables across ecozones. Sites are classified into ecozones along the x-axis, the value of the measured environmental variable for each lake is given along the y-axis.

Illustration A.2.4. Scatterplot of ^{13}C DOC vs. DOC ppm with oxidation of DOC trendline. This figure illustrates that there is enrichment due to the biodegradation of organics within the lakes. Lake P40-1 plots away from the main cluster of samples.

Illustration A.2.5 – Trends in nutrients and selected anions across ecozones. Sites are classified into ecozones along the x-axis, the values of the measured environmental variable for each lake is given along the y-axis. Open circles represent the second lake/site where two lakes/sites share the same portage (e.g. P54-1 closed, P54-2 open).

Illustration A.2.6. – Trends in elements across ecozones. Sites are classified into ecozones along the x-axis, the value of the measured environmental variable for each lake is given along the y-axis. Open circles represent the second lake/site where two lakes/sites share the same portage (e.g. P54-1 closed, P54-2 open).

Illustration A.2.7. Principal components analysis (PCA) of March 2010 sediment-water interface samples and environmental parameters. Sample sites listed as portage numbers (i.e. P (ortage) 26). Environmental variables: ALK-alkalinity, DIC-dissolved inorganic carbon, DOC-dissolved organic carbon, DO-dissolved oxygen, Lat-latitude,, NH3-Ammonia, NO3-nitrite, TP-total phosphorus, TN-total nitrogen.

A.3 Tables

Table A.3.1. Geographical co-ordinates and vegetational zonations of the 20 study sites.

♦ = Boreal Forest, Δ = Sparse Trees, • = Arctic Tundra

	SITE	LAT(N)	LONG(W)		SITE	LAT(N)	LONG(W)
♦	P26-1	63°23.297	112°51.768	•	P48-1	64°14.592	110°06.995
♦	P27-1	63°28.616	112°50.972	•	P49-1	64°15.571	110°05.878
♦	P28-1	63°23.974	112°50.514	•	P51-1	64°16.605	110°05.015
♦	P30-1	63°25.195	112°41.314	•	P52-1A	64°17.394	110°03.694
♦	P33-1	63°27.551	112°32.785	•	P52-1B	64°17.381	110°03.701
♦	P34-2	63°28.547	112°32.250	•	P53-1A	64°19.921	109°59.921
♦	P39-1	63°35.141	112°18.393	•	P53-1B	64°22.554	110°00.944
♦	P40-1	63°35.615	112°17.649	•	P54-1	64°24.717	110°06.199
Δ	P46-1	63°44.963	111°18.560	•	P54-2	64°25.114	110°06.449
Δ	P47-1	63°44.538	111°12.957	•	P55-1	64°25.794	110°08.168

Table A.3.2. Sample treatment in the field.

Analysis	Bottle	Filter	Preserve
Cations & Dissolved Metals	60 mL HDPE	Y	Nitric Acid
Anions	60 mL HDPE	Y	No
Stable Isotopes	60 mL HDPE	Y	No
Total Nutrients	2x125 mL HDPE	N	Sulphuric
DIC	40 mL amber w/ septum	Y	No
DOC	40 mL amber w/ septum	Y	No

Table A.3.3 Comparison of significant differences (two-tailed t-test results) of measured variables across the three vegetational zones [Boreal Forest (BF), Sparse-Trees (ST), Arctic Tundra (AT)]. Highlighted numbers indicates significantly different ($p < 0.05$). DO = Dissolved Oxygen. TKN = Total Kjeldalh Nitrogen. P-acid = Acid Extracted Phosphorous. TP = Total phosphorous. DOC = Dissolved Organic Carbon. DIC = Dissolved Inorganic Carbon.

Variable		BF vs ST	ST vs AT	BF vs AT
Depth	(m)	0.4641	0.3045	0.8010
DO	(%)	0.2479	0.6721	0.0115
DO	(mg/L)	0.2640	0.6367	0.0111
NH ₃	(µg/g)	0.5921	0.3148	0.0133
TKN	(µg/g)	0.4607	0.3822	0.0001
P-acid	(µg/g)	0.0671	0.1620	0.5483
TP	(µg/g)	0.6535	0.4957	0.0171
Temp	(°C)	0.7340	0.6468	0.1955
Alkalinity	(ppm)	0.0549	0.8099	0.0544
Conductivity	(µS/cm)	0.0567	0.4942	0.1416
DOC	(ppm)	0.1100	0.0907	0.1715
DIC	(ppm)	0.0922	0.4349	0.1775
δ ¹³ C DOC	(vpdb)	0.0332	0.0755	0.4066
δ ¹³ C DIC	(vpdb)	0.2303	0.3493	0.0851
Br	(ppm)	0.1086	0.0002	0.9652
Cl	(ppm)	0.0805	0.4398	0.3941
F	(ppm)	0.0472	0.0136	0.0000
NO ₃	(ppm)	0.2367	0.9035	0.2394
SO ₄	(ppm)	0.8029	0.3368	0.3233
pH	(units)	0.0157	0.0331	0.4196
Al	(ppb)	0.1565	0.0691	0.2078
As	(ppb)	0.1671	0.1118	0.7588
B	(ppb)	0.0012	0.1439	0.0235
Ba	(ppb)	0.0977	0.3553	0.2262
Ca	(ppm)	0.0917	0.9264	0.0966
Ce	(ppb)	0.1520	0.3453	0.1678
Cl	(ppm)	0.0472	0.4661	0.2600
Co	(ppb)	0.2618	0.2414	0.2532
Cr	(ppb)	0.0852	0.1966	0.1690
Cs	(ppb)	0.0871	0.0317	0.6645
Cu	(ppb)	0.0810	0.0068	0.2268
Fe	(ppm)	0.2117	0.2551	0.3867
Gd	(ppb)	0.0974	0.0738	0.1264
K	(ppm)	0.0506	0.4969	0.1159

Table A.3.3 (cont.)

Variable		BF vs ST	ST vs AT	BF vs AT
La	(ppb)	0.1380	0.6492	0.1449
Li	(ppb)	0.1915	0.2369	0.6300
Mg	(ppm)	0.0760	0.4438	0.2286
Mn	(ppb)	0.1826	0.4198	0.4277
Na	(ppm)	0.0205	0.7401	0.0263
Nd	(ppb)	0.1372	0.4888	0.1504
Ni	(ppb)	0.1717	0.0444	0.2758
Pb	(ppb)	0.0470	0.0983	0.0955
Pr	(ppb)	0.1364	0.4693	0.1497
Rb	(ppb)	0.1020	0.4135	0.2738
S	(ppm)	0.4470	0.2383	0.5207
Si	(ppm)	0.0381	0.4077	0.0583
Sm	(ppb)	0.1174	0.2042	0.1422
Sr	(ppb)	0.1655	0.7254	0.1482
U	(ppb)	0.0001	0.3151	0.0001
V	(ppb)	0.1291	0.1172	0.1977
Y	(ppb)	0.0813	0.1231	0.1105
Yb	(ppb)	0.0901	0.1518	0.1219
Zn	(ppb)	0.0210	0.0388	0.0823

Table A.2.4. Pearson Correlation matrix for measured environmental variables (following transformation) of the 18 lakeset. Light grey and dark grey indicate significant correlations at $P < 0.05$ and $P < 0.01$, respectively, based on Bonferroni-adjusted probabilities.

	DEPTH	AREA	TEMP	pH	ALK	COND	DO	DIC	DOC	TP	TKN	NH3	Al	As	B	Ba	Ca	Ce	Cl	Cs	Cu	Fe	K	Li	Mg	Mn	Na	Pb	Pr	S	Si	U	Zn	
Parameters	1.00																																	
	AREA	0.18																																
	TEMP	0.52	-0.39	1.00																														
	pH	0.07	0.07	-0.19	1.00																													
	ALK	-0.64	-0.44	-0.01	-0.10	1.00																												
	COND	-0.76	-0.48	-0.28	-0.18	0.84	1.00																											
	DO	0.54	0.54	0.03	0.19	-0.73	-0.81	1.00																										
	DIC	-0.72	-0.55	-0.06	-0.20	0.76	0.89	-0.77	1.00																									
	DOC	-0.68	-0.60	-0.19	-0.11	0.73	0.90	-0.82	0.90	1.00																								
	TP	0.13	-0.18	0.14	-0.26	0.34	0.29	-0.18	0.29	0.20	1.00																							
	TKN	-0.10	-0.55	0.27	-0.16	0.58	0.48	-0.38	0.55	0.48	0.81	1.00																						
	NH3	0.01	-0.45	0.33	0.09	0.55	0.32	-0.21	0.30	0.25	0.49	0.73	1.00																					
	Al	-0.52	-0.61	-0.19	0.00	0.61	0.76	-0.86	0.72	0.88	0.11	0.36	0.10	1.00																				
	As	-0.66	-0.44	-0.49	-0.03	0.48	0.81	-0.63	0.73	0.82	-0.01	0.14	0.00	0.76	1.00																			
	B	-0.68	-0.54	-0.09	-0.34	0.73	0.90	-0.80	0.82	0.79	0.32	0.51	0.21	0.69	0.62	1.00																		
	Ba	-0.80	-0.48	-0.34	-0.16	0.82	0.95	-0.80	0.89	0.91	0.20	0.45	0.26	0.80	0.85	0.80	1.00																	
	Ca	-0.50	-0.23	-0.17	-0.17	0.88	0.98	-0.81	0.90	0.90	0.33	0.57	0.41	0.76	0.75	0.87	0.95	1.00																
	Ce	-0.60	-0.52	-0.21	-0.01	0.78	0.85	-0.90	0.78	0.88	0.22	0.47	0.27	0.94	0.71	0.77	0.87	0.88	1.00															
	Cl	-0.69	-0.21	-0.28	-0.29	0.74	0.77	-0.39	0.62	0.58	0.24	0.32	0.42	0.29	0.56	0.61	0.70	0.74	0.44	1.00														
	Cs	-0.56	-0.53	-0.23	0.02	0.29	0.48	-0.51	0.57	0.61	-0.18	0.09	-0.16	0.66	0.70	0.41	0.63	0.44	0.51	0.15	1.00													
Cu	-0.37	-0.33	-0.21	-0.20	0.34	0.54	-0.55	0.56	0.66	0.13	0.18	0.04	0.61	0.65	0.47	0.59	0.50	0.59	0.32	0.47	1.00													
Fe	-0.61	-0.61	-0.29	-0.05	0.67	0.85	-0.79	0.76	0.85	0.17	0.39	0.16	0.93	0.85	0.76	0.87	0.84	0.92	0.49	0.62	0.56	1.00												
K	-0.74	-0.47	-0.32	-0.17	0.79	0.98	-0.76	0.86	0.89	0.31	0.47	0.30	0.73	0.82	0.88	0.91	0.96	0.82	0.77	0.45	0.63	0.83	1.00											
Li	-0.70	-0.57	-0.33	-0.02	0.57	0.87	-0.64	0.82	0.86	0.09	0.29	0.12	0.72	0.93	0.75	0.86	0.82	0.70	0.60	0.71	0.59	0.82	0.89	1.00										
Mg	-0.75	-0.51	-0.28	-0.15	0.80	0.99	-0.84	0.89	0.90	0.25	0.44	0.28	0.78	0.84	0.90	0.94	0.97	0.85	0.72	0.53	0.55	0.86	0.97	0.90	1.00									
Mn	-0.50	-0.62	-0.05	-0.17	0.68	0.82	-0.78	0.83	0.82	0.25	0.49	0.31	0.79	0.78	0.70	0.87	0.82	0.81	0.50	0.54	0.55	0.86	0.76	0.76	0.82	1.00								
Na	-0.64	-0.52	-0.15	-0.21	0.86	0.94	-0.79	0.83	0.89	0.40	0.61	0.46	0.75	0.65	0.87	0.87	0.96	0.86	0.74	0.30	0.52	0.78	0.94	0.73	0.91	0.74	1.00							
Pb	-0.50	-0.49	-0.12	-0.20	0.60	0.65	-0.69	0.63	0.73	0.11	0.30	0.13	0.81	0.63	0.58	0.71	0.66	0.81	0.41	0.53	0.76	0.80	0.67	0.59	0.64	0.65	0.67	1.00						
Pr	-0.54	-0.48	-0.21	0.01	0.76	0.82	-0.87	0.73	0.82	0.25	0.47	0.28	0.92	0.67	0.72	0.82	0.86	0.99	0.42	0.43	0.53	0.91	0.79	0.64	0.82	0.78	0.84	0.79	1.00					
S	-0.59	-0.08	-0.41	0.00	0.40	0.63	-0.56	0.44	0.39	-0.02	-0.10	-0.16	0.38	0.57	0.63	0.54	0.52	0.45	0.42	0.38	0.32	0.50	0.62	0.62	0.68	0.40	0.42	0.30	0.42	1.00				
Si	-0.56	-0.76	0.07	-0.15	0.83	0.83	-0.87	0.83	0.89	0.29	0.63	0.42	0.88	0.62	0.80	0.84	0.87	0.91	0.50	0.56	0.49	0.85	0.79	0.69	0.82	0.81	0.87	0.77	0.88	0.30	1.00			
U	-0.14	-0.52	0.24	-0.20	0.65	0.51	-0.55	0.46	0.57	0.49	0.72	0.69	0.53	0.15	0.51	0.44	0.59	0.63	0.40	-0.04	0.27	0.47	0.49	0.20	0.46	0.43	0.75	0.51	0.65	-0.14	0.73	1.00		
Zn	-0.58	-0.38	-0.17	-0.33	0.62	0.69	-0.77	0.70	0.72	0.30	0.44	0.05	0.76	0.55	0.77	0.73	0.71	0.80	0.36	0.46	0.67	0.74	0.70	0.54	0.70	0.64	0.71	0.78	0.77	0.38	0.74	0.48	1.00	

A.4 Maps

Illustration A.4.1 - Map showing sample locations and biogeographical regions: Boreal Forest (A), Sparse Trees (B), and Tundra (C) from the 2010 field season along the TCWR in the Northwest Territories as well as the 2009 field area near Yellowknife (map from Google Earth).

Illustration A.4.2 - Map showing an enlargement of the area surrounding the Lockhart Camp. Coring sites from the 2010 field season are shown.

Illustration A.4.3 - Map showing enlargement of the area surrounding Lac de Gras

Camp. Coring sites from the 2010 field are shown.

A.5 Water Property Data

Illustration A.5.1 - Temperature and dissolved oxygen depth profiles. Refer to Appendix A.5 – Table A.5.1 for data.

Illustration A.5.1 (cont.)

Illustration A.5.1 (cont.)

Table A.4.1 Water quality data. Units: meters (m), degrees Celsius (°C), percent (%), milligrams per liter (mg/L), microSiemens

Lake	Parameters		Depth (m)												
			0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6
Boreal Forest															
26.1	Temperature	(°C)	0.8	0.4	0.6	1.1	1.8	1.9	2.7	3	3.1				
	Dissolved Oxygen	(%)	75	92.5	98.3	101	96.6	94	92.4	88.2	84.9				
		(mg/L)	10.7	13.3	14	14.2	13.4	12.7	12.5	11.9	11.2				
	pH	(units)	7.68												
	Conductivity	(µS/cm)	18.7	18.7	18.9	18.7	18.5	18.5	18.5	18.5	18.7				
27.1	Temperature	(°C)	0.4	0.3	0.4	0.9									
	Dissolved Oxygen	(%)	60.6	61.3	62.1	61.8									
		(mg/L)	8.67	9.04	9.02	8.88									
	pH	(units)	7.29												
	Conductivity	(µS/cm)	26.8	25.2	24.9	25									
28.1	Temperature	(°C)	0.4	0.3	0.4	1	1.7	2.1	2.6	3.1	3.2				
	Dissolved Oxygen	(%)	67	82.9	82.9	86.7	79.4	76.5	73.5	69.9	41.6				
		(mg/L)	9.65	12	12.2	12.4	11	10.5	9.91	9.34	5.79				
	pH	(units)	7.28												
	Conductivity	(µS/cm)	18.6	19.1	19.5	19.8	19.8	20	20.1	20.3	20.9				
30.1	Temperature	(°C)	0.1	0.2	0.4	1.2	1.7	2.5	3.1	3.4	3.6	3.9	4	4.3	
	Dissolved Oxygen	(%)	83.8	83.6	84.3	80.1	82	88	79.6	71.5	54	49.2	36	5.4	
		(mg/L)	12.41	11.9	12	12.1	11.3	12	10.5	9.3	7.07	6.41	4.62	0.69	
	pH	(units)	7.14												
	Conductivity	(µS/cm)	14.9	14.8	14.8	14.8	14.7	14	14.8	15	15.5	16	16.5	19	
33.1	Temperature	(°C)	0	0.1	0.2	0.3	1.2	1.7							
	Dissolved Oxygen	(%)	39.4	33.5	33.6	32.6	31.3	12.1							
		(mg/L)	5.62	4.93	4.92	4.75	4.43	1.49							
	pH	(units)	6.75												
	Conductivity	(µS/cm)	33	33	32.8	33.2	35.2	45.8							
34.2	Temperature	(°C)	0.2	0.2	0.2	0.7	1.2	1.7	2.1	2.6	2.9	3.3			
	Dissolved Oxygen	(%)	68.2	88.8	97	96.6	93.1	94.6	67	56.2	69.6	9.4			
		(mg/L)	9.91	13	13.3	14.5	13.7	13.1	10.2	7.68	9.29	1.23			
	pH	(units)	6.61												
	Conductivity	(µS/cm)	12.8	22.7	27.4	27.4	27	27.1	27.3	27.4	28.2	32.8			
39.1	Temperature	(°C)	0.2	0.4	0.6										
	Dissolved Oxygen	(%)	6.1	5.2	4.5										
		(mg/L)	0.88	0.76	0.63										
	pH	(units)	6.31												
	Conductivity	(µS/cm)	43.9	43.7	44.2										
40.1	Temperature	(°C)	0.4	0.4	0.4	0.4	0.4	0.4							
	Dissolved Oxygen	(%)	20.3	10.5	8.1	5.6	5	4.7							
		(mg/L)	3.06	1.45	1.16	0.79	0.7	0.67							
	pH	(units)	6.41												
	Conductivity	(µS/cm)	93	95.3	95.1	95.7	95.9	95.9							
Sparse Trees															
46.1	Temperature	(°C)	0.1	0.1	0.1	0.3	0.5	0.7	0.8	1	1	1			
	Dissolved Oxygen	(%)	132.5	130	130	130	127	125	125	118	120	109			
		(mg/L)	19.31	19	19	18.9	18.4	18	18	16.8	17.1	16.2			
	pH	(units)	7.54												
	Conductivity	(µS/cm)	13.5	13.4	13.6	14.6	14.5	14.5	14.4	14.1	14.1	14.1			
47.1	Temperature	(°C)	0.8	0.6	0.6	0.7	1.3	1.7	2.1	2.6					
	Dissolved Oxygen	(%)	82.7	87.9	87.6	88.6	94.4	91.3	87.6	65.8					
		(mg/L)	12.07	12.7	12.8	12.7	13.2	12.6	12.1	9.07					
	pH	(units)	7.73												
	Conductivity	(µS/cm)	17.1	16.5	16.4	16.6	16.4	16.3	15.5	15.2					

Table A.4.1 (cont.)

Table A.9.1 (Cont.)																
Lake	Parameters		Depth (m)													
			0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5
Tundra																
48.1	Temperature (°C)		0.1	0.1	0.1	0.3										
	Dissolved Oxygen	(%)	36.5	38.5	37.7	36.6										
		(mg/L)	5.29	5.61	5.45	5.34										
	pH		6.99													
	Conductivity	(μS/cm)	21.7	22.1	22	21.9										
49.1	Temperature (°C)		0.5	0.6	0.7											
	Dissolved Oxygen	(%)	35.8	34.8	35.4											
		(mg/L)	5.14	5.02	5.06											
	pH		7.7													
	Conductivity	(μS/cm)	21.9	21.9	22.4											
51.1	Temperature (°C)		0.5	0.3	0.4	0.8										
	Dissolved Oxygen	(%)	33.9	7.6	6.7	5.4										
		(mg/L)	4.41	1.08	0.93	0.75										
	pH		6.56													
	Conductivity	(μS/cm)	64.2	64.3	64.1	64.6										
52.1	Temperature (°C)		1.2	0.7	0.6	0.6	1.3	1.9	2.2	2.6						
	Dissolved Oxygen	(%)	89.5	87.9	88	89.2	89.3	89.3	89.4	90.6						
		(mg/L)	12.72	12.8	12.8	12.8	12.6	12.4	12.2	12.1						
	pH		7.7													
	Conductivity	(μS/cm)	12.1	12.6	12.6	12.6	12.4	12.1	12	11.8						
53.1A	Temperature (°C)		0.3	0.2	0.2	0.2	0.3	0.3	0.4	0.5	0.4	0.5	0.5	0.6	0.6	0.6
	Dissolved Oxygen	(%)	129.2	128	127	126	126	125	126	126	124	123	124	122	117	118
		(mg/L)	18.65	18.6	18.5	18.4	18.2	18.2	18.2	18.3	18.8	17.8	17.8	17.5	16.9	16.9
	pH		9.22													
	Conductivity	(μS/cm)	8.2	8	7.8	7.7	7.2	7.3	7.2	7	6.7	6.5	6.5	6.4	6.3	6.4
53.1B	Temperature (°C)		0.1	0.1	0.1	0.2	0.3	0.3	0.4	0.5	0.6	0.8				
	Dissolved Oxygen	(%)	81.5	83.3	85.7	86.5	87.6	88.6	89.7	90.2	90.8	82.6				
		(mg/L)	11.89	12.2	12.6	12.6	12.7	12.9	12.9	13	13.1	10.9				
	pH		7													
	Conductivity	(μS/cm)	8	8	7.9	7.7	7.6	7.5	7.2	7.1	7.3	9.7				
54.1	Temperature (°C)		1.1	0.7	0.6	0.8	1.5	2	2.4	2.5						
	Dissolved Oxygen	(%)	108.1	107	106	107	105	103	98.6	86.7						
		(mg/L)	15.28	15.4	15.3	15.2	14.7	14.1	13.3	11.1						
	pH		6.57													
	Conductivity	(μS/cm)	13.4	13.3	13.1	13.1	12.9	12.5	12.1	12						
54.2	Temperature (°C)		0.9	0.8	0.7	0.7	1	1.5								
	Dissolved Oxygen	(%)	89.2	88.3	88.5	89.2	88.7	87.9								
		(mg/L)	12.75	12.7	12.7	12.8	12.5	12.1								
	pH		7.11													
	Conductivity	(μS/cm)	11.8	11.7	11.6	11.6	11.9	11.8								
55.1	Temperature (°C)		0.1		0.1		0.2		0.3		0.3					
	Dissolved Oxygen	(%)	89.5		95.2		94.5		99.9		103					
		(mg/L)	13.25		14		13.3		14.5		15					
	pH		7.38													
	Conductivity	(μS/cm)	14		13.8		13.7		13.1		13.3					

Table A.5.2 – ICP-MS and ICP-ES data from surface and bottom water samples

LAKE	Al		As		B		Ba		Ce		Co		Cr	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
(ppb)														
BOREAL FOREST														
26.1	11.300	10.000	0.240	0.190	2.350	1.915	3.370	4.440	0.052	0.046	0.025	0.025	0.140	0.145
27.1	18.500	17.900	0.265	0.260	3.050	2.970	6.290	5.890	0.145	0.140	0.025	0.025	0.185	0.180
28.1	18.850	16.100	0.260	0.300	2.140	2.070	5.810	5.600	0.133	0.129	0.052	0.053	0.220	0.200
30.1	61.800	50.000	0.220	0.180	2.290	2.280	4.030	5.150	0.376	0.303	0.025	0.172	0.230	0.220
33.1	35.500	38.800	0.200	0.240	4.405	5.080	5.785	6.970	0.464	0.520	0.057	0.071	0.245	0.280
34.2	55.700	51.950	0.240	0.215	5.030	4.165	3.820	3.815	0.444	0.439	0.025	0.025	0.300	0.240
39.1	231.400	227.900	0.550	0.580	3.120	3.780	17.220	17.710	2.212	2.265	0.936	0.796	0.790	0.800
40.1	732.800	727.350	1.560	1.510	3.910	3.835	32.010	31.580	6.141	6.051	4.384	4.409	1.800	1.775
MIN	11.300	10.000	0.200	0.180	2.140	1.915	3.370	3.815	0.052	0.046	0.025	0.025	0.140	0.145
MAX	732.800	727.350	1.560	1.510	5.030	5.080	32.010	31.580	6.141	6.051	4.384	4.409	1.800	1.775
MEDIAN	45.600	44.400	0.250	0.250	3.085	3.375	5.798	5.745	0.410	0.371	0.039	0.062	0.238	0.230
MEAN	145.731	142.500	0.442	0.434	3.287	3.262	9.792	10.144	1.246	1.236	0.691	0.697	0.489	0.480
SPARSE TREES														
46.1	7.200	2.500	0.250	0.180	2.275	1.490	3.880	3.190	0.126	0.029	0.025	0.025	0.050	0.050
47.1	11.650	6.300	0.240	0.190	1.925	1.370	4.510	3.760	0.178	0.072	0.068	0.059	0.100	0.100
MIN	7.200	2.500	0.240	0.180	1.925	1.370	3.880	3.190	0.126	0.029	0.025	0.025	0.050	0.050
MAX	11.650	6.300	0.250	0.190	2.275	1.490	4.510	3.760	0.178	0.072	0.068	0.059	0.100	0.100
MEDIAN	9.425	4.400	0.245	0.185	2.100	1.430	4.195	3.475	0.152	0.051	0.047	0.042	0.075	0.075
MEAN	9.425	4.400	0.245	0.185	2.100	1.430	4.195	3.475	0.152	0.051	0.047	0.042	0.075	0.075
ARCTIC TUNDRA														
48.1	17.400	14.100	0.380	0.310	2.790	2.690	8.220	7.720	0.255	0.174	0.420	0.231	0.130	0.140
49.1	47.550	46.000	0.850	0.800	3.165	3.280	5.900	5.620	0.178	0.122	0.358	0.362	0.330	0.310
51.1	89.700	79.800	1.220	1.170	4.780	4.350	19.850	19.440	0.508	0.466	2.627	2.499	0.670	0.630
52.1A	15.600	6.100	0.450	0.160	1.940	1.000	4.180	1.750	0.114	0.016	0.086	0.025	0.050	0.050
52.1B	13.600	6.800	0.320	0.170	1.660	1.200	2.590	1.800	0.082	0.018	0.025	0.025	0.050	0.050
53.1A	16.500	35.950	0.200	0.265	1.650	0.900	2.780	2.230	0.101	0.115	0.025	0.117	0.120	0.210
53.1B	8.300	6.250	0.210	0.140	1.390	1.225	2.960	2.265	0.051	0.020	0.025	0.025	0.050	0.050
54.1	11.050	7.700	0.290	0.230	2.420	2.010	4.495	3.930	0.042	0.023	0.025	0.025	0.115	0.100
54.2	17.400	7.650	0.530	0.240	2.430	2.075	3.920	3.960	0.085	0.029	0.087	0.127	0.050	0.050
55.1	4.400	2.400	0.550	0.250	1.460	1.370	3.170	2.800	0.036	0.015	0.025	0.025	0.050	0.050
MIN	4.400	2.400	0.200	0.140	1.390	0.900	2.590	1.750	0.036	0.015	0.025	0.025	0.050	0.050
MAX	89.700	79.800	1.220	1.170	4.780	4.350	19.850	19.440	0.508	0.466	2.627	2.499	0.670	0.630
MEDIAN	16.050	7.675	0.415	0.245	2.180	1.690	4.050	3.365	0.093	0.026	0.056	0.071	0.083	0.075
MEAN	24.150	21.275	0.500	0.374	2.369	2.010	5.807	5.152	0.145	0.100	0.370	0.346	0.162	0.164
FULL LAKESET														
MIN	4.400	2.400	0.200	0.140	1.390	0.900	2.590	1.750	0.036	0.015	0.025	0.025	0.050	0.050
MAX	732.800	727.350	1.560	1.510	5.030	5.080	32.010	31.580	6.141	6.051	4.384	4.409	1.800	1.775
MEDIAN	17.400	15.100	0.278	0.240	2.385	2.073	4.338	4.200	0.139	0.118	0.039	0.056	0.135	0.163
MEAN	71.310	68.078	0.451	0.379	2.709	2.453	7.240	6.981	0.586	0.550	0.466	0.456	0.284	0.282

Table A.5.2 (cont.)

LAKE	Cs		Cu		Gd		La		Li		Mn		Nd	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
(ppb)														
BOREAL FOREST														
26.1	0.013	0.012	0.520	0.320	0.008	0.007	0.038	0.037	2.308	2.071	1.220	11.940	0.037	0.036
27.1	0.018	0.017	0.555	0.530	0.017	0.016	0.097	0.087	2.875	2.722	4.880	5.180	0.096	0.092
28.1	0.018	0.016	1.020	7.780	0.010	0.011	0.080	0.078	2.788	2.763	17.470	18.980	0.067	0.065
30.1	0.020	0.020	1.370	0.970	0.037	0.030	0.223	0.177	1.574	1.427	3.620	47.470	0.224	0.177
33.1	0.013	0.013	1.015	0.920	0.043	0.048	0.328	0.346	2.886	2.969	12.050	17.800	0.276	0.302
34.2	0.016	0.013	1.450	1.325	0.041	0.040	0.322	0.313	3.791	3.360	1.740	4.690	0.268	0.268
39.1	0.033	0.032	2.490	2.990	0.128	0.130	1.126	1.147	4.959	4.999	89.830	89.710	1.007	1.012
40.1	0.067	0.066	3.780	3.485	0.332	0.322	3.092	3.050	13.471	13.146	284.320	283.375	2.684	2.695
MIN	0.013	0.012	0.520	0.320	0.008	0.007	0.038	0.037	1.574	1.427	1.220	4.690	0.037	0.036
MAX	0.067	0.066	3.780	7.780	0.332	0.322	3.092	3.050	13.471	13.146	284.320	283.375	2.684	2.695
MEDIAN	0.018	0.017	1.195	1.148	0.039	0.035	0.273	0.245	2.880	2.866	8.465	18.390	0.246	0.222
MEAN	0.025	0.024	1.525	2.290	0.077	0.075	0.663	0.654	4.331	4.182	51.891	59.893	0.582	0.581
SPARSE TREES														
46.1	0.013	0.011	0.780	0.500	0.006	0.003	0.069	0.024	2.349	2.192	4.965	1.730	0.055	0.022
47.1	0.012	0.011	0.745	0.490	0.011	0.003	0.109	0.051	2.491	2.204	10.435	17.540	0.099	0.051
MIN	0.012	0.011	0.745	0.490	0.006	0.003	0.069	0.024	2.349	2.192	4.965	1.730	0.055	0.022
MAX	0.013	0.011	0.780	0.500	0.011	0.003	0.109	0.051	2.491	2.204	10.435	17.540	0.099	0.051
MEDIAN	0.012	0.011	0.763	0.495	0.009	0.003	0.089	0.038	2.420	2.198	7.700	9.635	0.077	0.036
MEAN	0.012	0.011	0.763	0.495	0.009	0.003	0.089	0.038	2.420	2.198	7.700	9.635	0.077	0.036
ARCTIC TUNDRA														
48.1	0.021	0.022	1.870	1.400	0.020	0.014	0.128	0.092	2.588	2.574	9.510	6.120	0.145	0.104
49.1	0.020	0.030	2.640	2.340	0.014	0.012	0.097	0.068	6.858	6.896	36.550	37.210	0.099	0.077
51.1	0.132	0.082	2.050	1.670	0.035	0.034	0.239	0.217	10.696	10.246	212.300	206.880	0.255	0.239
52.1A	0.017	0.019	1.240	0.780	0.009	0.003	0.061	0.005	2.689	1.523	5.100	0.930	0.058	0.010
52.1B	0.031	0.018	1.770	0.520	0.005	0.003	0.040	0.010	2.077	1.710	1.680	0.580	0.037	0.011
53.1A	0.015	0.018	1.210	0.825	0.007	0.016	0.056	0.055	1.922	1.470	1.530	4.670	0.052	0.064
53.1B	0.011	0.029	0.800	0.830	0.003	0.003	0.031	0.012	1.754	1.587	0.650	0.355	0.028	0.014
54.1	0.019	0.030	1.150	0.800	0.003	0.003	0.024	0.013	3.316	2.926	1.470	2.590	0.027	0.016
54.2	0.019	0.023	1.380	0.990	0.007	0.003	0.045	0.017	3.065	2.987	5.850	19.275	0.042	0.018
55.1	0.014	0.005	1.350	0.850	0.003	0.003	0.018	0.005	1.577	1.732	9.160	1.280	0.021	0.011
MIN	0.011	0.005	0.800	0.520	0.003	0.003	0.018	0.005	1.577	1.470	0.650	0.355	0.021	0.010
MAX	0.132	0.082	2.640	2.340	0.035	0.034	0.239	0.217	10.696	10.246	212.300	206.880	0.255	0.239
MEDIAN	0.019	0.022	1.365	0.840	0.007	0.003	0.051	0.015	2.639	2.153	5.475	3.630	0.047	0.017
MEAN	0.030	0.028	1.546	1.101	0.010	0.009	0.074	0.049	3.654	3.365	28.380	27.989	0.076	0.056
FULL LAKESET														
MIN	0.011	0.005	0.520	0.320	0.003	0.003	0.018	0.005	1.574	1.427	0.650	0.355	0.021	0.010
MAX	0.132	0.082	3.780	7.780	0.332	0.322	3.092	3.050	13.471	13.146	284.320	283.375	2.684	2.695
MEDIAN	0.018	0.019	1.295	0.885	0.010	0.011	0.088	0.062	2.739	2.648	5.475	9.030	0.082	0.064
MEAN	0.026	0.024	1.459	1.516	0.037	0.035	0.311	0.290	3.802	3.575	35.717	38.915	0.279	0.264

Table A.5.2 (cont.)

LAKE	Ni		Pb		Pr		Rb		Sm		Sr		U	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
(ppb)														
BOREAL FOREST														
26.1	0.190	0.190	0.047	0.022	0.009	0.009	1.821	1.597	0.008	0.008	15.040	13.755	0.800	0.742
27.1	0.190	0.190	0.029	0.017	0.023	0.022	2.259	2.142	0.019	0.018	20.305	19.390	1.045	1.023
28.1	0.190	0.190	0.109	0.225	0.017	0.017	2.763	2.789	0.012	0.014	15.345	15.290	1.063	1.040
30.1	0.800	0.830	0.067	0.017	0.055	0.045	2.274	2.121	0.041	0.034	9.870	10.590	0.904	0.685
33.1	0.295	0.290	0.145	0.087	0.072	0.078	2.460	2.591	0.052	0.056	23.255	24.720	1.356	1.461
34.2	0.600	0.480	0.115	0.050	0.070	0.069	2.658	2.295	0.047	0.047	16.610	15.950	0.863	0.690
39.1	1.390	1.350	0.848	0.342	0.266	0.266	3.956	3.934	0.163	0.165	45.600	42.360	0.454	0.458
40.1	3.200	3.050	0.240	0.190	0.702	0.689	7.936	7.760	0.434	0.429	88.190	87.405	1.501	1.474
MIN	0.190	0.190	0.029	0.017	0.009	0.009	1.821	1.597	0.008	0.008	9.870	10.590	0.454	0.458
MAX	3.200	3.050	0.848	0.342	0.702	0.689	7.936	7.760	0.434	0.429	88.190	87.405	1.501	1.474
MEDIAN	0.448	0.385	0.112	0.068	0.063	0.057	2.559	2.443	0.044	0.040	18.458	17.670	0.974	0.883
MEAN	0.857	0.821	0.200	0.119	0.152	0.149	3.266	3.153	0.097	0.096	29.277	28.683	0.998	0.946
SPARSE TREES														
46.1	0.305	0.290	0.075	0.005	0.015	0.006	1.997	1.846	0.009	0.003	13.850	13.100	0.120	0.055
47.1	0.315	0.310	0.089	0.016	0.025	0.013	1.989	1.785	0.015	0.007	15.790	15.030	0.105	0.076
MIN	0.305	0.290	0.075	0.005	0.015	0.006	1.989	1.785	0.009	0.003	13.850	13.100	0.105	0.055
MAX	0.315	0.310	0.089	0.016	0.025	0.013	1.997	1.846	0.015	0.007	15.790	15.030	0.120	0.076
MEDIAN	0.310	0.300	0.082	0.011	0.020	0.009	1.993	1.816	0.012	0.005	14.820	14.065	0.113	0.065
MEAN	0.310	0.300	0.082	0.011	0.020	0.009	1.993	1.816	0.012	0.005	14.820	14.065	0.113	0.065
ARCTIC TUNDRA														
48.1	3.670	3.780	0.108	0.046	0.036	0.026	2.670	2.673	0.025	0.019	17.810	18.010	0.037	0.021
49.1	2.485	2.540	0.135	0.030	0.024	0.017	3.313	3.332	0.017	0.013	15.730	15.830	0.066	0.036
51.1	5.640	5.020	0.157	0.102	0.063	0.059	5.684	5.570	0.045	0.042	47.770	44.510	0.069	0.059
52.1A	0.550	0.250	0.107	0.018	0.014	0.003	1.775	1.072	0.010	0.003	9.310	4.640	0.047	0.060
52.1B	0.410	0.290	0.404	0.016	0.010	0.003	1.483	1.179	0.005	0.003	5.920	4.930	0.064	0.028
53.1A	0.540	0.430	0.077	0.051	0.013	0.027	1.545	1.134	0.009	0.023	6.280	4.755	0.059	0.057
53.1B	0.470	0.395	0.055	0.017	0.007	0.003	1.366	1.238	0.005	0.003	5.910	5.115	0.069	0.063
54.1	0.880	0.760	0.090	0.013	0.006	0.003	2.203	1.868	0.005	0.003	10.280	9.050	0.033	0.024
54.2	0.840	0.915	0.090	0.012	0.012	0.003	2.102	2.013	0.009	0.003	8.210	8.320	0.048	0.026
55.1	0.770	0.980	0.120	0.005	0.006	0.003	1.823	1.867	0.003	0.003	10.190	11.120	0.056	0.061
MIN	0.410	0.250	0.055	0.005	0.006	0.003	1.366	1.072	0.003	0.003	5.910	4.640	0.033	0.021
MAX	5.640	5.020	0.404	0.102	0.063	0.059	5.684	5.570	0.045	0.042	47.770	44.510	0.069	0.063
MEDIAN	0.805	0.838	0.108	0.018	0.012	0.003	1.963	1.868	0.009	0.003	9.750	8.685	0.057	0.047
MEAN	1.626	1.536	0.134	0.031	0.019	0.014	2.396	2.194	0.013	0.011	13.741	12.628	0.055	0.044
FULL LAKESET														
MIN	0.190	0.190	0.029	0.005	0.006	0.003	1.366	1.072	0.003	0.003	5.910	4.640	0.033	0.021
MAX	5.640	5.020	0.848	0.342	0.702	0.689	7.936	7.760	0.434	0.429	88.190	87.405	1.501	1.474
MEDIAN	0.575	0.455	0.108	0.020	0.020	0.017	2.231	2.067	0.014	0.013	15.193	14.393	0.087	0.062
MEAN	1.187	1.127	0.155	0.064	0.072	0.068	2.704	2.540	0.047	0.044	20.063	19.194	0.438	0.407

Table A.5.2 (cont.)

LAKE	V		Y		Yb		Zn		Ca		Cl	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
(ppb)						(ppm)						
BOREAL FOREST												
26.1	0.050	0.120	0.034	0.032	0.003	0.003	1.570	0.995	3.101	2.911	1.320	1.145
27.1	0.100	0.050	0.070	0.068	0.006	0.006	2.385	1.860	4.252	4.132	1.585	1.480
28.1	0.185	0.220	0.046	0.044	0.003	0.003	8.695	3.300	3.082	3.064	1.485	1.340
30.1	0.130	0.150	0.162	0.149	0.014	0.014	6.560	3.010	2.384	2.513	0.350	0.330
33.1	0.155	0.330	0.220	0.229	0.018	0.018	3.830	4.630	5.346	5.641	1.230	1.320
34.2	0.170	0.160	0.193	0.177	0.017	0.017	6.850	2.415	3.901	3.840	0.690	0.620
39.1	0.830	0.930	0.483	0.475	0.044	0.042	6.520	9.800	8.939	8.838	1.020	1.040
40.1	2.530	2.440	1.231	1.217	0.099	0.099	5.220	3.380	18.358	18.077	1.760	1.680
MIN	0.050	0.050	0.034	0.032	0.003	0.003	1.570	0.995	2.384	2.513	0.350	0.330
MAX	2.530	2.440	1.231	1.217	0.099	0.099	8.695	9.800	18.358	18.077	1.760	1.680
MEDIAN	0.163	0.190	0.178	0.163	0.016	0.016	5.870	3.155	4.076	3.986	1.275	1.233
MEAN	0.519	0.550	0.305	0.299	0.025	0.025	5.204	3.674	6.170	6.127	1.180	1.119
SPARSE TREES												
46.1	0.155	0.050	0.022	0.005	0.003	0.003	7.390	0.920	2.370	2.238	0.785	0.600
47.1	0.155	0.050	0.030	0.016	0.003	0.003	3.355	0.770	2.725	2.518	0.820	0.700
MIN	0.155	0.050	0.022	0.005	0.003	0.003	3.355	0.770	2.370	2.238	0.785	0.600
MAX	0.155	0.050	0.030	0.016	0.003	0.003	7.390	0.920	2.725	2.518	0.820	0.700
MEDIAN	0.155	0.050	0.026	0.011	0.003	0.003	5.373	0.845	2.547	2.378	0.803	0.650
MEAN	0.155	0.050	0.026	0.011	0.003	0.003	5.373	0.845	2.547	2.378	0.803	0.650
ARCTIC TUNDRA												
48.1	0.170	0.120	0.064	0.047	0.003	0.003	7.360	3.560	3.476	3.571	1.100	1.110
49.1	0.260	0.190	0.078	0.067	0.008	0.008	6.495	2.790	3.226	3.139	0.475	0.520
51.1	0.570	0.520	0.171	0.158	0.018	0.017	21.960	2.450	8.546	8.587	2.310	2.250
52.1A	0.350	0.050	0.040	0.005	0.003	0.003	3.040	1.000	1.731	0.818	0.830	0.450
52.1B	0.200	0.050	0.026	0.005	0.003	0.003	6.110	0.620	1.025	0.851	0.610	0.450
53.1A	0.050	0.180	0.032	0.069	0.003	0.006	4.890	1.330	1.054	0.798	0.420	0.280
53.1B	0.050	0.050	0.018	0.005	0.003	0.003	2.430	0.930	0.978	0.858	0.340	0.340
54.1	0.050	0.050	0.017	0.011	0.003	0.003	2.605	2.510	1.732	1.534	0.755	0.630
54.2	0.190	0.050	0.033	0.015	0.003	0.003	2.750	0.845	1.385	1.415	0.660	0.625
55.1	0.310	0.050	0.012	0.005	0.003	0.003	1.790	0.680	1.352	1.472	1.460	1.370
MIN	0.050	0.050	0.012	0.005	0.003	0.003	1.790	0.620	0.978	0.798	0.340	0.280
MAX	0.570	0.520	0.171	0.158	0.018	0.017	21.960	3.560	8.546	8.587	2.310	2.250
MEDIAN	0.195	0.050	0.033	0.013	0.003	0.003	3.965	1.165	1.558	1.443	0.708	0.573
MEAN	0.220	0.131	0.049	0.039	0.005	0.005	5.943	1.672	2.450	2.304	0.896	0.803
Full Lakeset												
MIN	0.050	0.050	0.012	0.005	0.003	0.003	1.570	0.620	0.978	0.798	0.340	0.280
MAX	2.530	2.440	1.231	1.217	0.099	0.099	21.960	9.800	18.358	18.077	2.310	2.250
MEDIAN	0.170	0.120	0.043	0.046	0.003	0.003	5.055	2.138	2.903	2.714	0.825	0.665
MEAN	0.333	0.291	0.149	0.140	0.013	0.013	5.590	2.390	3.948	3.841	1.000	0.914

Table A.5.2 (cont.)

LAKE	Fe		K		Mg		Na		S		Si	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
(ppm)												
BOREAL FOREST												
26.1	0.015	0.041	0.987	0.840	1.086	0.979	2.098	1.869	0.329	0.295	0.459	0.496
27.1	0.170	0.180	1.223	1.189	1.419	1.395	2.667	2.604	0.415	0.402	0.887	0.894
28.1	0.064	0.065	1.220	1.327	1.176	1.172	2.314	2.272	0.353	0.374	0.572	0.592
30.1	0.024	0.064	0.713	0.637	1.133	1.066	1.576	1.374	0.604	0.490	0.785	0.895
33.1	0.402	0.445	1.480	1.534	2.310	2.371	3.563	3.733	1.306	1.358	1.069	1.149
34.2	0.097	0.163	1.775	1.601	2.100	2.058	3.429	3.114	1.713	1.577	0.767	1.041
39.1	2.542	2.608	2.030	2.047	3.081	3.062	4.569	4.563	0.995	0.986	3.065	3.023
40.1	9.259	9.476	3.674	3.522	6.275	6.199	8.903	8.643	1.077	1.060	5.448	5.287
MIN	0.015	0.041	0.713	0.637	1.086	0.979	1.576	1.374	0.329	0.295	0.459	0.496
MAX	9.259	9.476	3.674	3.522	6.275	6.199	8.903	8.643	1.713	1.577	5.448	5.287
MEDIAN	0.133	0.172	1.351	1.431	1.759	1.726	3.048	2.859	0.800	0.738	0.836	0.968
MEAN	1.572	1.630	1.638	1.587	2.322	2.288	3.640	3.522	0.849	0.818	1.631	1.672
SPARSE TREES												
46.1	0.010	0.005	0.887	0.799	0.976	0.943	1.081	0.958	0.779	0.727	0.115	0.089
47.1	0.069	0.039	0.903	0.761	1.093	0.982	1.139	0.929	0.798	0.632	0.190	0.216
MIN	0.010	0.005	0.887	0.761	0.976	0.943	1.081	0.929	0.779	0.632	0.115	0.089
MAX	0.069	0.039	0.903	0.799	1.093	0.982	1.139	0.958	0.798	0.727	0.190	0.216
MEDIAN	0.039	0.022	0.895	0.780	1.035	0.962	1.110	0.944	0.788	0.680	0.153	0.153
MEAN	0.039	0.022	0.895	0.780	1.035	0.962	1.110	0.944	0.788	0.680	0.153	0.153
ARCTIC TUNDRA												
48.1	0.073	0.072	1.235	1.246	1.459	1.506	1.310	1.336	1.449	1.495	0.174	0.169
49.1	0.579	0.621	1.448	1.427	1.971	1.929	1.472	1.441	0.959	0.933	0.255	0.251
51.1	4.110	3.995	2.406	2.348	4.939	4.967	2.783	2.699	3.201	3.281	1.850	1.840
52.1A	0.023	0.005	0.745	0.418	0.994	0.494	0.846	0.462	0.859	0.432	0.207	0.106
52.1B	0.010	0.005	0.589	0.452	0.622	0.518	0.669	0.515	0.575	0.481	0.123	0.096
53.1A	0.017	0.260	0.610	0.440	0.604	0.467	0.626	0.447	0.639	0.500	0.136	0.127
53.1B	0.005	0.005	0.541	0.500	0.560	0.497	0.551	0.539	0.612	0.560	0.118	0.112
54.1	0.023	0.018	0.822	0.732	1.037	0.926	0.914	0.813	0.826	0.715	0.173	0.171
54.2	0.031	0.019	0.811	0.767	0.871	0.875	0.854	0.815	0.913	0.856	0.204	0.207
55.1	0.019	0.005	0.877	0.843	0.883	0.925	1.174	1.119	1.021	1.012	0.042	0.031
MIN	0.005	0.005	0.541	0.418	0.560	0.467	0.551	0.447	0.575	0.432	0.042	0.031
MAX	4.110	3.995	2.406	2.348	4.939	4.967	2.783	2.699	3.201	3.281	1.850	1.840
MEDIAN	0.023	0.018	0.817	0.749	0.939	0.900	0.884	0.814	0.886	0.785	0.173	0.148
MEAN	0.489	0.500	1.008	0.917	1.394	1.310	1.120	1.019	1.105	1.026	0.328	0.311
Full Lakeset												
MIN	0.005	0.005	0.541	0.418	0.560	0.467	0.551	0.447	0.329	0.295	0.042	0.031
MAX	9.259	9.476	3.674	3.522	6.275	6.199	8.903	8.643	3.201	3.281	5.448	5.287
MEDIAN	0.047	0.065	0.945	0.841	1.113	1.024	1.391	1.355	0.843	0.721	0.231	0.234
MEAN	0.877	0.905	1.249	1.171	1.730	1.666	2.127	2.012	0.971	0.908	0.832	0.840

Table A.5.3 – Dissolved organic and inorganic carbon, nutrients (bottom samples only) and geochemistry of surface and bottom water samples.

LAKE	C DOC		C DIC		$\delta^{13}\text{C}$ DOC	$\delta^{13}\text{C}$ DOC	$\delta^{13}\text{C}$ DIC	$\delta^{13}\text{C}$ DIC	Ammonia (N) Total	Kjeldahl Nitrogen	Phosphorus (NaHCO3)	Phosphorus Total
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom				
ppm												
vpdb												
(µg/g)												
BOREAL FOREST												
26.1	9.05	7.73	5.83	7.46	-25.94	-26.46	-10.6	-13.51	12.5	17700	35	1720
27.1	10.83	9.94	10.15	9.2	-26.06	-25.18	-12.46	-12.25	38.9	18400	49	973
28.1	9.89	11	4.52	9.95	-26.57	-25.88	-9.25	-14.22	59.5	15400	11	1420
30.1	9.96	8.75	5.9	8.09	-26.56	-25.19	-12.43	-15.47	13.2	13400	22	1090
33.1	9.35	9.89	13.93	10.2	-25.26	-25.98	-13.66	-12.72	44.4	15000	25	889
34.2	14.26	11.54	8.39	9.11	-26.22	-26.52	-11.64	-15.08	6.46	10500	25	1890
39.1	27.13	32.53	19.79	21.54	-26.43	-26.61	-16.12	-15.97	3.39	5740	7.9	523
40.1	92.94	94.73	45.35	49.05	-27.08	-26.98	-18.16	-16.87	42.6	18800	25	809
MIN	9.050	7.730	4.520	7.460	-27.080	-26.980	-18.160	-16.870	3.390	5740.000	7.900	523.000
MAX	92.940	94.730	45.350	49.050	-25.260	-25.180	-9.250	-12.250	59.500	18800.000	49.000	1890.000
MEDIAN	10.395	10.470	9.270	9.575	-26.325	-26.220	-12.445	-14.650	26.050	15200.000	25.000	1031.500
MEAN	22.926	23.264	14.233	15.575	-26.265	-26.100	-13.040	-14.511	27.619	14367.500	24.988	1164.250
SPARSE TREES												
46.1	4.07	3.43	5.1	4.6	-25.21	-24.36	-9.62	-8.68	22.7	5450	7.9	650
47.1	5.67	4.2	7.82	6.41	-23.73	-24.93	-10.01	-11.75	68.2	13500	15	1260
MIN	4.070	3.430	5.100	4.600	-25.210	-24.930	-10.010	-11.750	22.700	5450.000	7.900	650.000
MAX	5.670	4.200	7.820	6.410	-23.730	-24.360	-9.620	-8.680	68.200	13500.000	15.000	1260.000
MEDIAN	4.870	3.815	6.460	5.505	-24.470	-24.645	-9.815	-10.215	45.450	9475.000	11.450	955.000
MEAN	4.870	3.815	6.460	5.505	-24.470	-24.645	-9.815	-10.215	45.450	9475.000	11.450	955.000
ARCTIC TUNDRA												
48.1	6.21	7.06	11.66	12.5	-24.83	-25.09	-13.85	-13.62	0.44	2560	28	732
49.1	15.41	14.28	13.91	13.3	-25.9	-26.44	-15.87	-15.91	0.81	5370	56	792
51.1	21.41	17.47	25.85	23.16	-26.01	-26.16	-15.17	-15.42	7.82	3490	27	535
52.1A	5.19	4.09	5.26	6.2	-24.73	-25.86	-13.44	-13.35	4.38	2260	13	480
52.1B	4.42	3.64	3.87	2.1	-26.19	-26.2	-11.64	-11.32	0.91	438	7.9	85.9
53.1A	3.32	2.82	2.37	1.26	-26.49	-26.32	-12.84	-11	1.5	1800	11	493
53.1B	3.5	3.38	2.54	1.9	-26.51	-26.57	-12.2	-10.66	4.05	4800	8	763
54.1	6.72	5.49	6.24	5.18	-26.09	-25.35	-13.09	-14.77	3.14	9120	12	1270
54.2	6.31	7.04	4.68	7.05	-24.24	-23.38	-12.93	-13.36	4.26	3760	25	411
55.1	3.73	3.75	3.73	1.95	-25.17	-26.2	-11.87	-10.06	5.01	1240	22	740
MIN	3.320	2.820	2.370	1.260	-26.510	-26.570	-15.870	-15.910	0.440	438.000	7.900	85.900
MAX	21.410	17.470	25.850	23.160	-24.240	-23.380	-11.640	-10.060	7.820	9120.000	56.000	1270.000
MEDIAN	5.700	4.790	4.970	5.690	-25.955	-26.180	-13.010	-13.355	3.595	3025.000	17.500	633.500
MEAN	7.622	6.902	8.011	7.460	-25.616	-25.757	-13.290	-12.947	3.232	3483.800	20.990	630.190
FULL LAKESET												
MIN	3.320	2.820	2.370	1.260	-27.080	-26.980	-18.160	-16.870	0.440	438.000	7.900	85.900
MAX	92.940	94.730	45.350	49.050	-23.730	-23.380	-9.250	-8.680	68.200	18800.000	56.000	1890.000
MEDIAN	7.885	7.395	6.070	7.775	-26.035	-26.070	-12.650	-13.435	5.735	5595.000	22.000	777.500
MEAN	13.469	13.138	10.345	10.511	-25.761	-25.783	-12.843	-13.300	17.209	8436.400	21.635	876.295

Table A.5.3 (cont.)

LAKE	Alkalinity		Br		Cl		Cond		F		NO3		pH		SO4	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
	(ppm)						(µS/cm)		(ppm)				(units)		(ppm)	
BOREAL FOREST																
26.1	11	11	0.021	0.026	1.128	1.025	33.64	33.6	0.1	0.091	0.019	0.145	6.41	6.61	0.776	0.71
27.1	17	16	0.022	0.019	1.41	1.342	44.64	42.3	0.121	0.119	0.05	0.044	7.04	7.03	1.038	1.002
28.1	14	13	0.029	0.071	1.309	1.221	36.53	36.24	0.082	0.092	0.061	0.019	6.64	6.68	0.784	0.817
30.1	8	9	0.03	0.02	0.2915	0.254	30.145	28.98	0.0665	0.059	0.1615	0.452	6.875	6.79	1.588	1.312
33.1	24	26	0.02	0.019	1.118	1.158	61.34	63.34	0.123	0.129	0.216	0.2	6.77	6.86	3.904	4.128
34.2	16	16	0.019	0.029	0.583	0.421	51.68	50.69	0.128	0.11	0.053	0.191	6.94	7.03	5.068	4.745
39.1	34	34	0.019	0.019	0.875	0.907	76.06	75.63	0.092	0.09	0.054	0.043	7.02	6.92	2.192	2.244
40.1	72	68	0.088	0.082	1.873	1.573	147.2	148.5	0.078	0.086	0.032	0.02	7.33	7.31	0.5	0.43
MIN	8.000	9.000	0.019	0.019	0.292	0.254	30.145	28.980	0.067	0.059	0.019	0.019	6.410	6.610	0.500	0.430
MAX	72.000	68.000	0.088	0.082	1.873	1.573	147.200	148.500	0.128	0.129	0.216	0.452	7.330	7.310	5.068	4.745
MEDIAN	16.500	16.000	0.022	0.023	1.123	1.092	48.160	46.495	0.096	0.092	0.054	0.095	6.908	6.890	1.313	1.157
MEAN	24.500	24.125	0.031	0.036	1.073	0.988	60.154	59.910	0.099	0.097	0.081	0.139	6.878	6.904	1.981	1.924
SPARSE TREES																
46.1	8	7	0.019	0.019	0.706	0.602	28.32	25.74	0.085	0.079	0.022	0.019	7.21	7.15	2.35	2.233
47.1	8	8	0.019	0.019	0.702	0.615	30.27	28.1	0.077	0.07	0.061	0.074	7.24	7.24	2.328	1.893
MIN	8.000	7.000	0.019	0.019	0.702	0.602	28.320	25.740	0.077	0.070	0.022	0.019	7.210	7.150	2.328	1.893
MAX	8.000	8.000	0.019	0.019	0.706	0.615	30.270	28.100	0.085	0.079	0.061	0.074	7.240	7.240	2.350	2.233
MEDIAN	8.000	7.500	0.019	0.019	0.704	0.609	29.295	26.920	0.081	0.075	0.042	0.047	7.225	7.195	2.339	2.063
MEAN	8.000	7.500	0.019	0.019	0.704	0.609	29.295	26.920	0.081	0.075	0.042	0.047	7.225	7.195	2.339	2.063
ARCTIC TUNDRA																
48.1	10	11	0.031	0.029	0.953	0.96	44.31	45.64	0.039	0.039	0.233	0.229	6.8	6.81	4.174	4.257
49.1	12.5	1	0.039	0.034	0.455	0.447	44.97	44.05	0.0355	0.041	0.028	0.019	6.785	6.8	2.4385	2.45
51.1	35	34	0.044	0.048	2.33	2.178	105.8	104.5	0.041	0.045	0.019	0.019	6.83	6.79	9.694	9.754
52.1A	4	2	0.031	0.038	0.571	0.499	26.76	14.3	0.028	0.017	0.182	0.035	7.08	7.11	2.457	1.21
52.1B	3	2	0.038	0.04	0.562	0.439	18.63	15.27	0.024	0.02	0.02	0.019	6.99	7	1.645	1.293
53.1A	2	2	0.027	0.021	0.372	0.249	16.94	14.12	0.032	0.019	0.019	0.019	7.24	7.27	1.763	1.345
53.1B	2	1	0.04	0.037	0.32	0.285	16.64	15.215	0.034	0.0195	0.019	0.019	7.03	6.995	1.651	1.468
54.1	5	7	0.04	0.034	0.653	0.529	27.63	25.3	0.024	0.024	0.106	0.067	7.02	6.98	2.236	1.965
54.2	3	4	0.025	0.025	0.575	0.774	25.06	25.93	0.03	0.026	0.087	0.052	7.14	7.11	2.514	2.557
55.1	4	3	0.042	0.046	1.284	1.219	27.1	27.69	0.022	0.022	0.054	0.034	7.05	6.96	2.87	2.789
MIN	2.000	1.000	0.025	0.021	0.320	0.249	16.640	14.120	0.022	0.017	0.019	0.019	6.785	6.790	1.645	1.210
MAX	35.000	34.000	0.044	0.048	2.330	2.178	105.800	104.500	0.041	0.045	0.233	0.229	7.240	7.270	9.694	9.754
MEDIAN	4.000	2.500	0.039	0.036	0.573	0.514	26.930	25.615	0.031	0.023	0.041	0.027	7.025	6.988	2.448	2.208
MEAN	8.050	6.700	0.036	0.035	0.808	0.758	35.384	33.202	0.031	0.027	0.077	0.051	6.997	6.983	3.144	2.909
FULL LAKESET																
MIN	2.000	1.000	0.019	0.019	0.292	0.249	16.640	14.120	0.022	0.017	0.019	0.019	6.410	6.610	0.500	0.430
MAX	72.000	68.000	0.088	0.082	2.330	2.178	147.200	148.500	0.128	0.129	0.233	0.452	7.330	7.310	9.694	9.754
MEDIAN	9.000	8.500	0.030	0.029	0.704	0.695	31.955	31.290	0.054	0.052	0.054	0.039	7.020	6.988	2.282	1.929
MEAN	14.625	13.750	0.032	0.034	0.904	0.835	44.683	43.257	0.063	0.060	0.075	0.086	6.972	6.972	2.599	2.430

A.6 Freeze Core Catalogue

Table A.6.1 – Sediment cores collected during the 2010 field season and lake metadata. Cores are ordered from south to north and are broken into three groups. Group A (Boreal Forest) lies below the southern limit of the treeline, Group B (Sparse Trees) lies between the southern and northern limits of the treeline, and Group C (Tundra) lies above the northern limit of the treeline.

Lake (#)	Surface Area (hectares)	Depth (m)	Core name	Coordinates (decimal minutes)	Corer Type	Face #	Sect #	Length (cm)	Figure #	
BOREAL FOREST										
P-26-1 (Bridge S)	119.5	4.5	ROAD10-BRIDGE1	N63°23.297	2F	1	1	60.9	CO1	
			ROAD10-BRIDGE2	W112°51.768	1F	1	1	64.8	CO2	
							1	45.1	CO3	
							2	53.5	CO4	
26-1-(2-4)			Glew		Top - Middle - Bottom					
P-27-1 (Bridge N)	11.9	2	27-1-(1-3)	N63°28.616 W112°50.972	Glew	Top - Middle - Bottom				
P-28-1	21.3	4.5	28-1-(2-4)	N63°23.974 W112°50.514	Glew	Top - Middle - Bottom				
P-30-1 (Pat's)	45	5.5	ROAD10-PAT'S LAKE	N63°25.195	1F	1	1	36.9	CO5	
			30-1-(2-4)	W112°41.314	Glew		2	34.6	CO6	
3	80.8	CO7								
Top - Middle - Bottom										
P-33-1 (Problem)	54	2.3	33-1-(2-4)	N63°27.551 W112°32.785	Glew	Top - Middle - Bottom				
P-34-2 (Danny's)	19.2	4.4	ROAD10-DANNY'S LAKE	N63°28.547 W112°32.25	2F	1	1	69.4	CO8	
							2	48.6	CO9	
							1	33.4	C10	
							2	37.8	C11	
							3	45	C12	
34-2-(2-4)			Glew		Top - Middle - Bottom					
P-39-1	37.3	1	ROAD10-39-1B	N63°35.103 W112°18.427	1F	1	1	29.3	C15	
		1.1	ROAD10-39-1A	N63°35.105 W112°18.436	2F	1	1	27.3	C13	
								2	27.9	C14
								Top - Middle - Bottom		
1.25			39-1-(2-4)	N63°35.141 W112°18.393	Glew	Top - Middle - Bottom				
P-40-1	11.1	1.5	40-1-(2-4)	N63°35.141 W112°17.649	Glew	Top - Middle - Bottom				
SPARSE TREES										
P-46-1 (Portage S)	1108.8	3.6	ROAD10-46-1	N63°44.963	2F	1	1	33.3	C16	
		2.5	46-1-(2-5)	W111°18.560	Glew	2	1	36.9	C17	
			46-1-(6-8)	N63°44.599 W111°14.486	Glew	Top - Middle - Bottom				
P-47-1 (Portage N)	194.9	4.85	ROAD10-47-1	N63°44.538	1F	1	1	40.4	C18	
			47-1-(2-4)	W111°12.957	Glew		2	45.3		
						Top - Middle - Bottom				

Notes: Two face freeze corer (2F), one face freeze corer (1F) and the Glew corer (Glew).

The number of sections that make up the freeze core were included (Sect #). For Glew cores, subsamples were taken from the surface (Top), the middle of the core (Middle), and the case of the core (Bottom). Units: meters (m), centimeters (cm).

Table A.6.1 (cont.)

Lake (#)	Surface Area (hectares)	Depth (m)	Core name	Coordinates (decimal minutes)	Corer 1F/2F	Face #	Sect #	Length (cm)	Figure #	
ARCTIC TUNDRA										
Mackay	97600	1.5	MK-(2*,3*,4,5)	N64°14.592 W110°06.995	Glew	T - M - B (* no middle collected)				
P-49-1	29.8	3.5	ROAD10-49-1A	N64°15.571 W110°05.878	2F	1	1	38	C19	
						2	2	32.8		
		1.5	49-1-(2-4)		Glew	Top - Middle - Bottom				
			ROAD10-49-1B	N64°17.76 W110°03.288	1F	1	1	60		C20
P-51-1	2.3	1.5	51-1-(2*,3,4)	N64°16.605 W110°05.015	Glew	T - M - B (* no middle collected)				
P-52-1 (Horseshoe)	505.1	4	ROAD10-52-1	N64°17.381 W110°03.701	2F	1	1	52.6	C22	
						2	2	49		
			52-1-(2 & 4-5)		Glew	2	1	55	C23	
			52-1-1-(2-3)		Glew		2	49.7	C24	
P-53-1 (Gravel Pit N)	531	6.5	53-1-(2-4)	N64°19.921 W109°59.921	Glew	Top - Middle - Bottom				
		4.25	53-1-2-(2-4)	N64°22 554, W110°00.944	Glew	Top - Middle - Bottom				
P-54-1 (Abe)	210.7	3.5	54-1-(2-4)	N64°24 717 W110°06.199	Glew	Top - Middle - Bottom				
P-54-2 (Echo)	45.7	3	ROAD10-ECHO	N64°25.114 W110°06.449	2F	1	1	44.5	C25	
							2	2		43.2
						2	1	52		
P-55-1 (Lac de Gras)	57800	4	ROAD10-Lacdegras	N64°25 794 W110°08.168	2F	1	1	44.7	C26	
						2	1	49.2	C27	
			LG-(2*,3-5)		Glew	T - M - B (* no middle collected)

Illustration A.6.01. Freeze core ROAD10-BRIDGE1, Face 1 of 2: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. Note: The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.02. Freeze core ROAD10-BRIDGE1, Face 2 of 2: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. Note: The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.03. Freeze core ROAD10-BRIDGE2, Face 1 of 1, Section 1 of 2: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. Note: The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.04. Freeze core ROAD10-BRIDGE2, Face 1 of 1, Section 2 of 2: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. Note: The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.05. Freeze core ROAD10-PAT'S LAKE, Face 1 of 1, Section 1 of 3: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. Note: The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm. Also note: knots from the wooden board below show up in the X-Ray images.

Illustration A.6.06. Freeze core ROAD10-PAT'S LAKE, Face 1 of 1, Section 2 of 3:

(left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm. Also note: knots from the wooden board below show up in the X-Ray images.

Illustration A.6.07. Freeze core ROAD10-PAT'S LAKE, Face 1 of 1, Section 3 of 3:

(left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.08. Freeze core ROAD10-DANNY'S LAKE, Face 1 of 2, Section 1 of 2: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.09. Freeze core ROAD10-DANNY'S LAKE, Face 1 of 2, Section 2 of 2: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.10. Freeze core ROAD10-DANNY'S LAKE, Face 2 of 2, Section 1 of 3: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.11. Freeze core ROAD10-DANNY'S LAKE, Face 2 of 2, Section 2 of 3: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.12. Freeze core ROAD10-DANNY'S LAKE, Face 2 of 2, Section 3 of 3: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.13. Freeze core ROAD10-39-1A, Face 1 of 2, Section 1 of 1: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.14. Freeze core ROAD10-39-1A, Face 2 of 2, Section 1 of 1: light photograph only.

Illustration A.6.15. Freeze core ROAD10-39-1B, Face 1 of 1, Section 1 of 1: light photograph only.

Illustration A.6.16. Freeze core ROAD10-46-1, Face 1 of 2, Section 1 of 1: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.17. Freeze core ROAD10-46-1, Face 2 of 2, Section 1 of 1: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.18. Freeze core ROAD10-47-1, Face 1 of 1, Section 1 of 2: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.19. Light photographs of freeze core ROAD10-49-1A. Face 1 of 2 (left), Sections 1 and 2 of 2. Face 2 of 2 (right), Sections 1 and 2 of 2.

Illustration A.6.20. Freeze core ROAD10-49-1B, Face 1 of 1, Section 1 of 2: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.21. Freeze core ROAD10-49-1B, Face 1 of 1, Section 2 of 2: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.22. Freeze core ROAD10-52-1, Face 1 of 2, Sections 1 & 2: (left) light photograph of Section 1; (right) light photograph of Section 2.

Illustration A.6.23. Freeze core ROAD10-52-1, Face 2 of 2, Section 1 of 2: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.24. Freeze core ROAD10-52-1, Face 2 of 2, Section 2 of 2: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.25. Freeze core ROAD10-ECHO, Face 1 of 2, Sections 1 & 2: (left) light photograph of Section 1; (right) light photograph of Section 2.

Illustration A.6.26. Freeze core ROAD10-Lacdegras, Face 1 of 2, Section 1 of 1: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

Illustration A.6.27. Freeze core ROAD10-Lacdegras, Face 2 of 2, Section 1 of 1: (left) light photograph; (middle) positive X-Ray; (right) negative X-Ray. The big bars on the X-Ray scale are separated by 5 cm and the small bars are separated by 1 cm.

A.7 Chronology

Table A.7.1. AMS radiocarbon dates from TCWR freeze cores.

Lake	Corer	Face	Sect	Sample ID	14 C Age (uncalibrated)	+/-	Depth (cm)	UBA (#)	Material Dated
Tibbitt	1F			1 TibA_20cm	67	22	20	UBA-17353	Bulk
				1 TibA_40cm	1409	20	40	UBA-17354	Bulk
				1 TibA_80cm	2046	26	80	UBA-17355	Bulk
				2 ROAD09-TIBBITT01-A55-55.5cm	2390	40	138.25		Bulk
Waite	1F			1 WAITE15	995	24	16.9	UBA-16433	Bulk
				1 WAITE25	1129	22	29.1	UBA-16434	Bulk
				1 WAITE39	1455	23	43.2	UBA-16435	Bulk
				1 WAITE53	1519	22	57.8	UBA-16436	Bulk
				1 ROAD09-WAITE01-A65-67.5cm	1520	40	66.3		Bulk
				2 WaiteB_110	2107	29	109.7	UBA-15638	Twig
				2 ROAD09-WAITE01-B79-81cm	2580	40	154		Bulk
				3 ROAD09-WAITE01-C22-23cm	2920	40	185		Bulk
				3 ROAD09-WAITE01-C-43-43.75cm	3460	40	205.1		Bulk
P34-2 (Danny's)	2F	2		1 P34-F2_5.7cm	693	21	5.7	UBA-17359	Bulk
				1 P34-F2_10.2cm	855	23	10.2	UBA-17360	Bulk
				1 Danny_2_1_ChipA	1329	23	15	UBA-16543	Bulk
				1 P34-F2_21.9cm	1617	25	21.9	UBA-17361	Bulk
				1 P34-F2_27.8	1659	21	27.8	UBA-17431	Bulk
				1 Danny_2_1_6/9	1916	25	32.6	UBA-16544	Bulk
				1 P34-F2_37.6cm	2659	32	37.6	UBA-17432	Bulk
				2 Danny_2_2_ChipB	2912	24	45	UBA-16545	Bulk
				2 Danny_2_2_132/135	3604	25	56.9	UBA-16546	Bulk
				2 Danny_2_2_5	5039	51	70.1	UBA-16547	Bulk
				3 Danny_2_3_ChipC	5834	29	85.1	UBA-16548	Bulk
				3 Danny_2_3_200	8112	32	95.5	UBA-16439	Bulk
				3 Danny_2_3_20	7450	30	113.6	UBA-16440	Bulk
P39-1A	2F	1		1 P39-1A-F1_10cm	3597	26	10	UBA-17344	Bulk
				1 P39-1A-F1_19cm	3701	24	19	UBA-17345	Bulk
				1 P39-1A-F1_29cm	5385	35	29	UBA-17346	Bulk
P47-1	2F	2		1 P47_13.5	4218	38	13.5	UBA-17159	Bulk
				1 P47_41	4885	37	41	UBA-17160	Bulk
				1 P47_63	5333	35	63	UBA-17161	Bulk
				1 P47_86.5	5878	34	86.5	UBA-17162	Bulk
P49-1B	1F			1 P49-1B-F1_19.5cm	1925	25	19.5	UBA-17347	Bulk
				2 P49-1B-F1_64.5cm	3675	24	64.5	UBA-17348	Bulk
				2 P49-1B-F1_100cm	5663	26	100	UBA-17349	Bulk
P52-1	2F	2		1 P52-F2_9cm	178	25	9	UBA-17350	Bulk
				1 P52_18	1148	42	18	UBA-17163	Bulk
				1 P52-F2_28cm	2763	22	28	UBA-17351	Bulk
				1 P52-F2_38cm	3343	23	38	UBA-17352	Bulk
				1 P52_45	5916	58	55	UBA-17165	Bulk
				2 P52_80	7488	40	80	UBA-17166	Bulk
				2 P52_106	8011	43	106	UBA-17167	Bulk
Lac de Gras	2F	2	1	LG-F2_19cm	3299	38	19	UBA-17356	Bulk
				LG-F2_32cm	1607	29	32	UBA-17357	Bulk
				LG-F2_46cm	2144	35	46	UBA-17358	Bulk
Note: UBA (#) is code that Chronos Lab (Queens University Belfast) gives to radiocarbon samples. Samples without a UBA code were submitted to Beta Analytic Inc. All dates are uncalibrated.

Illustration A.7.1 – Age-depth relationships of Road 10 freeze cores generated using Clam software (version 1.0.2; Blaauw, 2010). Linear models with all dates included. All ages are calibrated radiocarbon dates, converted to calendar years before present using IntCal09 (Reimer et al., 2009).

Appendix B - Chapter 2 Materials

B.1 Illustrations

Illustration B.1.1 & B.1.2 – Sledge microtome schematics

Illustration B.1.1 - CAD image of cutter assembly attached to table assembly of the freeze core sledge microtome. Parts of the microtome: metal ramp (a), plastic cutting board (b), brass spike (c), plastic clip (d), knife holder (e), pivot (f), rod (g), crank wheel (h), bolt (i), metal foot (j), sediment cutter foot (k), adjustable pin (l), vice screws (m), blade (n), block (o) and sediment core section (p).

Illustration B.1.2 - CAD image of cutter assembly.

Illustration B.1.3 - Photograph of freeze core sledge microtome with sediment core section attached.

Illustration B.1.3 - Photograph of freeze core sledge microtome with sediment core section attached.

Appendix C - Chapter 3 Materials

C.1 Illustrations

Illustration C.1.1 – Map of the study area

Illustration C.1.1 - Map of the study area. The survey samples are not marked on the map. They cover an area as delineated by Point 1 (furthest west and south), Point 6 (furthest east) and Point 10 (furthest North). Figure originally appeared in Crann et al. (2015).

Illustration C.1.2 – Bathymetric Maps

Illustration C.1.2 – Bathymetric maps of Carleton Lake (above) and Danny's Lake (below). Coring sites are denoted by an arrow for Carleton Lake and a box for Danny's Lake. Bathymetric maps were kindly provided by Tetra Tech EBA.

Illustration C.1.3 – Age-depth model

Illustration C.1.3 – Age-depth models. Details are discussed in Crann et al. (2015). Danny's Lake was constructed using BACON version 2.2 that uses the IntCal13 calibration curve. Mean accumulation rates were entered as a priori in Bacon, based on a summary of accumulation rates by Crann et al. (2015). A Bayesian outlier analysis was performed using the general outlier model (Bronk Ramsey 2009b) on a sequence in OxCal version 4.1 (Bronk Ramsey 2009a). The outlier analysis performed in OxCal identified five outliers in the Danny's Lake core that were omitted. Carleton Lake was constructed using CLAM using the IntCal09 calibration curve (Reimer et al., 2009). The year the core was collected was added as the age of the sediment-water interface with an error of ± 5 years. A smoothing parameter of 0.3 was employed. Radiocarbon ages younger than AD1950 were calibrated in CALIBomb. Figure originally appeared in (Crann et al. 2015).

Illustration C.1.4 – Grain-size frequency distributions and EM loadings

Illustration C.1.4 – (on following page) Results of robust end-member modeling for the studied lakes showing both the original grain-size distributions (lighter grey) and the rEM loadings. For the rEMs the mean and $\pm \sigma$ are plotted.

Illustration C.1.5 – EM stratigraphic profiles

Illustration C.1.5 - Stacked profiles of rEM abundances in the Danny's Lake (above) and Carleton Lake (below) cores.

C.2 Tables

Table C.2.1 - Lake Physical Information

Lake system	Latitude [°N]	Longitude [°E]	Present Altitude [m a.s.l.]	Lake Size [km ²]	Catchment Size [km ²]	References on lake systems and catchments
Danny's	63.48	112.54	420	0.22	0.99	(Macumber et al. 2012)
Carleton	64.26	110.09	417	0.31	1.4	(Upiter et al. 2014)

Table C.2.2 – Lake Water Column Properties

Lake	Season	Depth (m)	Temperature (°C)	Dissolved O (%)	Conductivity
Danny's	August 2011	0	14.5	86.2	34.8
		3.5	14.5	83.7	34.8
	March 2010	0	0.5	97	27.4
		4	2.9	69.6	28.2
Carleton	August 2011	0	15.1	98	9.3
		3.5	15	92.2	9.3
	March 2010	0	0.5	35.8	11.0
		1	0.7	35.4	11.2

Table C.2.3 - Sediment Core Information. Latitude and longitude are in decimal degrees.

* represents maximum depth of the lake.

Lake system	Sediment core name	Latitude [°N]	Longitude [°W]	Core length [m]	Time period [ka]	Water depth [m]	Distance to shore [km]
Danny's	P34-2-2FTF2	63.48	-112.54	1.2	8.3	4.4 (9*)	0.12
Carleton	P49-2FRF2	64.26	-110.10	1.1	2.4	4	0.18

Table C.2.4 - Table of radiocarbon dates submitted for each core. Originally published in (Crann et al. 2015). AMS – accelerated mass spectroscopy.

Lake information	Lab ID	Method	Depth (cm)	^{14}C age (BP) $\pm 1\sigma$	Material dated	Cal yBP $\pm 2\sigma$
Danny's Lake (P34-2) collected in 2010 <i>face two of two</i>	UBA-17359	AMS	5.7	693 $\pm$ 21	Bulk	567–679
	UBA-17360	AMS	10.2	855 $\pm$ 23	Bulk	695–795
	UBA-16543	AMS	15–15.5	1329 $\pm$ 23	Bulk	1184–1299
	UBA-17361	AMS	21.9	1617 $\pm$ 25	Bulk	1416–1556
	UBA-17431	AMS	27.8	1659 $\pm$ 21	Bulk	1521–1615
	UBA-16544	AMS	32.6	1916 $\pm$ 25	Bulk	1818–1904
	UBA-20377	AMS	33.5	2071 $\pm$ 24	Bulk	1987–2120
	UBA-20378	AMS	34.2	2159 $\pm$ 24	Bulk	2061–2305
	UBA-17929	AMS	34.5	2257 $\pm$ 26	Bulk	2158–2343
	UBA-20376	AMS	35.3	2073 $\pm$ 28	Bulk	1986–2124
	UBA-20375	AMS	36.8	2248 $\pm$ 25	Bulk	2158–2339
	UBA-17432	AMS	37.6	2659 $\pm$ 32	Bulk	2742–2884
	UBA-20374	AMS	38.4	2392 $\pm$ 25	Bulk	2345–2488
	UBA-20373	AMS	39.3	2448 $\pm$ 33	Bulk	2358–2702
	UBA-17930	AMS	40.4	2549 $\pm$ 26	Bulk	2503–2748
	UBA-20371	AMS	41.4	2554 $\pm$ 28	Bulk	2503–2750
	UBA-20372	AMS	43.3	4863 $\pm$ 29	Bulk	5583–5652
	UBA-16545	AMS	45–45.5	2912 $\pm$ 24	Bulk	2964–3157
	UBA-16546	AMS	56.9	3604 $\pm$ 25	Bulk	3845–3975
	UBA-16547	AMS	70.1	5039 $\pm$ 51	Bulk	5661–5903
	UBA-16548	AMS	85–85.5	5834 $\pm$ 29	Bulk	6560–6733
	UBA-17931	AMS	89.5	6231 $\pm$ 34	Bulk	7016–7253
	UBA-16439	AMS	95.5	8112 $\pm$ 32	Bulk	8997–9125
	UBA-17932	AMS	99.1	7623 $\pm$ 38	Bulk	8370–8518
	UBA-16440	AMS	113.6	7450 $\pm$ 30	Bulk	8191–8346
	TO-3313	AMS	75–77	7640 $\pm$ 100	Moss	8206–8627
Carleton Lake (R12-P49) collected in 2012 <i>face two of two</i>	UBA-20612	AMS	10.0	702 $\pm$ 39	Bulk	560–699
	UBA-20613	AMS	36.2	1337 $\pm$ 31	Bulk	1181–1305
	UBA-20614	AMS	55.3	1302 $\pm$ 46	Bulk	1132–1304
	UBA-20615	AMS	81.5	2132 $\pm$ 31	Bulk	2002–2299
	UBA-20616	AMS	117.8	2944 $\pm$ 32	Bulk	2989–3216

Table C.2.5 - Input and boundary parameters for similarly-likely EM model runs for rEM

calculation and optimal EMMA ($l_{\max}$ and l_{opt} refer to maximum and optimal weight quantiles; q_{opt} indicates optimal number of EMs; see text).

Site/core	No. of samples	No. of non-zero grain-size classes	$l_{\max}$	l_{opt}	No. of included models	No. of rEM	Total R^2_{mean}	q_{opt}
Lake Survey	51	66	0.06	0.02	918	4	0.83	4
Danny's Lake	558	50	0.06	0.00	714	3	0.91	3
Carleton Lake	169	47	0.15	0.00	255	2	0.84	2

Table C.2.6 - Grain-size parameters of rEM within each dataset. Secondary modes were not included in the description.

Dataset	EM#	Variance (%)	Mean (μm)	Mode (μm)	Description	Presence (%)	Abundance (%)
Lake Survey	01	33	13.7	6.5	Fine Silt	84.3	37.2 (27.2)
	02	11	14.1	13.6	Fine Silt	84.3	44.7 (24.9)
	03	26	71.3	69.6	Very Fine Sand	41.2	14.2 (25.0)
	04	30	157.6	161.2	Fine Sand	7.8	2.6 (14.0)
Danny	01	53	9.3	7.9	Fine Silt	56.0	0.28 (0.39)
	02	17	40.2	43.7	Coarse Silt	81.9	0.70 (0.38)
	03	30	167.1	154.0	Fine Sand	7.4	0.02 (0.09)
Carleton	01	50	7.5	7.8	Very Fine Silt	92.9	0.85 (0.30)
	02	50	129.5 (38.9)	127.8	Fine Sand (Coarse Silt)	25.4	0.11 (0.23)

Table C.2.7 - The relationship between rEMs and environmental parameters was evaluated using dependence tests. For parameters that were normally distributed a Pearson's product correlation coefficient was used. For parameters that were non-normally distributed a Kendall's rank coefficient was used. C:N – Carbon to Nitrogen ratio; DO – Dissolved oxygen; Cond – Conductivity; TOC – Total organic carbon; SA – Surface area.

Parameter	Positive correlation ($p < 0.05$; * $p < 0.01$)	Negative correlation ($p < 0.05$; * $p < 0.01$)
6.5 μm		Al*, Na*, C:N
14 μm	Al, Cu, Fe, Ni, Zn	
70 μm	Na*, Al	Depth
170 μm		
Northing	As*, DO	Cond*, TOC*, Zn*, Ni
Surface Area	Depth*	C:N, Zn
Depth	SA*, Fe*	C:N, Zn
Conductivity	TOC	North*, DO*, K*
C:N	TOC*, Cu, Ni, Zn	SA
TOC	Cu*, Cd*, Zn*, C:N*, Cond*, Ni	North*, Depth
DO	North	Cond*, Mn*, Depth, Fe
Al	Na*, K*, Mn*, Cd, Fe	
K	Na*, Al*	TOC*, Cu*, S*, P*, COND*, Pb, Ni
Na	K*, Al*	Mg
S	TOC*, Cu*, Zn*, Ni*, C:N*, Cond	North*, K*, Depth

Table C.2.8 - Results of principle component analysis of rEM datasets. Results for the 14 μm rEM are not shown as it was not well constrained by the model. TOC – total organic carbon, C:N – ratio of carbon to nitrogen, COND – conductivity, DO – dissolved oxygen, SA – surface area.

rEM	PC	Eigenvalue	Variance Explained	Positive Loadings	Negative Loadings
6.5 μm	1	1.9897	0.2843	TOC, C:N	Depth
6.5 μm	2	1.7684	0.2526	Na	6.5 μm
6.5 μm	3	1.4110	0.2016	Cond	DO, 6.5 μm
70 μm	1	2.1547	0.3591	70 μm , DO	Fe, Depth
70 μm	2	1.1838	1.973	Na	DO
70 μm	3	1.0379	0.1730	Cond	Depth
161 μm	1	2.3391	0.3342	TOC, C:N	Depth
161 μm	2	1.4612	0.2087	SA, Depth	Na, 161 μm
161 μm	3	1.0460	0.1494	C:N, Depth	DO

Appendix D - Chapter 4 Materials

D.1 Illustrations

Illustration D.1.1 – Location of study sites

Illustration D.1.1 – Location of sampling sites.

Illustration D.1.2 – R-mode vs. Q-mode cluster diagram for the 42 samples with statistically significant Arcellinida counts. Four faunal assemblages are indicated. The *dashed lines* demarcate clusters of samples with correlation coefficients greater than the selected level of significance. C. Mills = Cedar Mills; Schom. = Schomberg Cemetery; Trump. = Trumpeter; M. Hope = Mount Hope; C. Meadows = Cedar Meadows.

Axis 2 (eigenvalue = 0.139)

Axis 1 (eigenvalue = 0.253)

VARIABLE	%	P <
Al	4.72	0.006
Depth	4.15	0.032
Ni	4.15	0.032
K	3.86	0.026
DO	3.86	0.046
P	3	0.136
ORP	2.86	0.164
Ca	2.86	0.176
Mn	2.72	0.202
Cond.	2.72	0.204
pH	2.43	0.266
Zn	2.29	0.314
Mode	2.15	0.36
Mg	2.15	0.36
Fe	2.15	0.364
Pb	2.15	0.378
Clay	1.86	0.496
Si	1.86	0.604
TOC	1.43	0.706
Intercor.	45.5	n / a

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Illustration D.1.4 – Results from substrate bias analysis

Illustration D.1.4 – (on the following page) A) Ternary plot of the 42 samples. Axes of the plot represent the abundance of certain grain sizes in the samples. Coarse Grain = 63 to 16 microns; Medium Grain = 16 to 4 microns; Fine Grain = 4 microns and smaller. Sample points are coded to represent relative abundance of *Diffflugia protaeiformis* Lamarck strain 'claviformis'. Above Average = greater than 1 standard deviation (SD); Average = 1 to -0.5 SD; Below Average = less than -0.5 SD; Barren = not present in the sample. (B-D) scatterplots of ternary plot axes versus percent abundance of both DPA (open circle) and DPC (closed circle). DPC is equally distributed throughout the sedimentary gradient and thus displays no substrate bias.

A)

B)

C)

D)

Illustration D.1.5 – Photoplate

Illustration D.1.5 - Scanning electron micrographs of tests from species treated in this study: **(A - E)** *Diffugia protaeiformis* Lamarck strain 'acuminata', **(F - H)** *Diffugia protaeiformis* Lamarck strain 'claviformis'. Hand drawn pictures of tests from species treated in this study: **(I - K)** *Diffugia pyriformis* var. claviformis Penard 1899, **(L)** *Diffugia protaeiformis* Lamarck. All scale bars represent 50 µm. The lines placed over **(D)** and **(I)** are spaced at 10 µm.

Appendix E - Chapter 5 Materials

E.1 Illustrations

Illustration E.1.1 – Map of the study area

Illustration E.1.1 Map of the study area. Figure originally appeared in Crann et al. (2015).

Illustration E.1.2 – Bathymetry profile of Carleton Lake

Illustration E.1.2 – Bathymetry profile of Carleton Lake with an arrow showing approximate coring site.

Illustration E.1.3 – Age-depth model of Carleton Lake core

Illustration E.1.3 – (on the following page) Bayesian age-depth model for Carleton Lake. On the *top panel*, the *leftmost plot* shows that the Markov Chain Monte Carlo runs were stable (1,200 iterations), the *middle plot shows* the prior (*curve*) and posterior (*filled distribution curve*) distribution for the accumulation rate (year/cm), and the rightmost plots show the prior (*curve*) and posterior (filled distribution curve) for the dependence of accumulation rate between sections. The *major plot* shows the age distribution of calibrated ^{14}C dates and the grey-scale age-depth model indicates precisely dated sections of the chronology in *darker grey*, whereas *lighter grey* indicate less precise sections. Originally presented in Crann et al. (2015).

Illustration E.1.4 – Stratigraphic profiles of results from Arcellinida analysis of Carleton Lake

Illustration E.1.4 – (on the following page) Arcellinida fractional abundance, test concentration (CC), Shannon Diversity Index (SDI) and principal components (PC) for Carleton Lake versus time (cal yBP). Significant changes in the chironomid assemblage as determined using constrained incremental sum of squares (CONISS) are shown as stratigraphic zones.

Illustration E.1.5 – Summary Stratigraphic Figure

Illustration E.1.5 – (on the following page) Summary stratigraphic figure comparing our study with previous studies. (A) Toronto Lake (MacDonald et al. 1993), (B) Lake TK20 Diatom Diversity Index (DI), (C) Queen’s Lake isotope-inferred mean annual temperature (MAT) (Edwards et al. 1996), (D) Queen’s Lake diatom-inferred dissolved organic carbon (DOC) (Pienitz et al. 1999), (E & F) Carleton Lake (L.) mean July air temperature (MJAT) inferred from the Barley and Porinchu chironomid-based transfer functions (TF) (Upiter et al. 2014), (G) Carleton Lake loss-on-ignition (LOI) inferred total organic carbon (TOC) (Upiter et al. 2014), (H-K) Carleton Lake principal component analysis (PCA) B axes scores (this study).

E.2 Tables

Table E.2.1 - Radiocarbon ages from all sites, calibrated with the IntCal13 calibration curve (Reimer et al. 2013) using Clam (Blaauw 2010). The year the core was collected is included as it was used to model the age of the sediment-water interface in the Clam age-depth models. Dates identified as outliers are shown in bold and radiocarbon dates younger than AD1950 are in italics.

Lake Information	Lab ID	Method	Depth (cm)	^{14}C age (BP) $\pm 1\sigma$	Material dated	Cal yBP $\pm 2\sigma$
Carleton Lake	<i>UBA-18472</i>	AMS	<i>0-0.05</i>	<i>1.0264 $\pm$ 0.0035</i>	<i>Bulk</i>	<i>AD 1955-1957</i>
	UBA-17934	AMS	10–10.5	1046 $\pm$ 24	Bulk	925–983
	UBA-17347	AMS	19.5–20	1925 $\pm$ 25	Bulk	1822–1926
	UBA-17935	AMS	40–40.5	2762 $\pm$ 35	Bulk	2780–2946
	UBA-17348	AMS	64.5–65	3675 $\pm$ 24	Bulk	3926–4087
	UBA-17936	AMS	80–80.5	4635 $\pm$ 32	Bulk	5304–5465
	UBA-17349	AMS	100–100.5	5663 $\pm$ 26	Bulk	6399–6497

Table E.2.2 - Results from Arcellinida enumeration in fractional abundances. SDI – Shannon Diversity Index, CeAA – *Centropyxis aculeata* (Ehrenberg 1832) strain “aculeata”, CeAD – *C. aculeata* (Ehrenberg 1832) strain “discoides”, CeCA – *C. constricta* (Ehrenberg 1843) strain “aerophila”, CeCS – *C. constricta* (Ehrenberg 1843) strain “spinosa”, CuT – *Cucurbitella tricusps* (Carter 1856), CyK – *Cyclopyxis kahli* (Deflandre 1929), DiAC – *Diffflugia acuminata* Ehrenberg 1838, DiACC – *D. acuminata* Ehrenberg 1838 strain “curvicaulis”, DiACW – *D. acuminata* Ehrenberg 1838 strain “wide”, DiAs – *D. acuminata* Ehrenberg 1838 strain “aspericolea”, DiE – *D. elegans* Penard 1890, DiGA – *D. glans* Penard 1902 strain “glans”, DiGm – *D. glans* Penard 1902 strain “magna”, DiGo – *D. globulosa* (Dujardin 1837) Penard 1902 strain “globulosa”, DiGP – *D. globulosa* (Dujardin 1837) Penard 1902 strain “parvus”, DiOE – *D. oblonga* Ehrenberg 1832 strain “elongata”, DiOL – *D. oblonga* Ehrenberg 1832 strain “lanceolata”, DiOO – *D. oblonga* Ehrenberg 1832 strain “oblonga”, DiOS – *D. oblonga* Ehrenberg 1832 strain “spinosa”, DiOTe – *D. oblonga* Ehrenberg 1832 strain “tenuis”, DiPr – *D. protaeiformis* Lamark 1816, DiSc – *D. scalpellum* Penard 1899, DiU – *D. urceolata* Carter 1864, LaV – *Lagenodiffflugia vas* Leidy 1874, LeS – *Lesquereusia spiralis* (Ehrenberg 1840), PoC – *Pontigulasia compressa* (Carter 1864), Sp7 – Unknown species 7.

Table E.2.2 (cont.)

Depth (cm)	Total Count	SDI	Tests per cc	Probably Error	CeAA	CeAD	CeCA	CeCS	CuT
0	365	1.99	876	3.77	0.022	0.077	0.090	0.000	0.000
0.5	266	1.76	638.4	6.05	0.000	0.041	0.102	0.000	0.000
1	340	1.76	816	4.19	0.000	0.065	0.068	0.000	0.000
1.5	320	1.92	768	4.59	0.000	0.069	0.072	0.000	0.000
2	264	2.00	669.6	5.63	0.000	0.064	0.064	0.000	0.034
2.5	346	1.89	895.2	3.64	0.000	0.061	0.029	0.000	0.000
3	333	1.83	799.2	4.32	0.000	0.036	0.069	0.000	0.000
3.5	281	1.67	674.4	5.57	0.000	0.000	0.071	0.000	0.000
4	344	2.02	902.4	3.60	0.000	0.032	0.023	0.000	0.000
4.5	289	1.56	348	5.32	0.000	0.000	0.055	0.000	0.000
5	219	1.67	525.6	8.10	0.000	0.000	0.050	0.000	0.000
5.5	205	1.60	492	8.94	0.000	0.000	0.049	0.000	0.000
6	337	2.07	404.4	4.24	0.000	0.050	0.045	0.000	0.047
6.5	311	1.66	373.2	4.79	0.000	0.000	0.077	0.000	0.000
7	229	1.76	274.8	7.58	0.000	0.000	0.066	0.000	0.000
7.5	205	2.03	492	8.94	0.000	0.000	0.073	0.000	0.039
8	231	2.02	559.2	7.38	0.000	0.039	0.052	0.000	0.000
8.5	336	1.99	403.2	4.26	0.000	0.036	0.068	0.000	0.033
9	299	1.61	239.2	5.08	0.000	0.040	0.050	0.000	0.030
9.5	300	2.11	240.8	5.03	0.000	0.030	0.060	0.000	0.027
10	317	1.86	760.8	4.65	0.000	0.041	0.050	0.000	0.038
11.5	362	2.25	434.4	3.81	0.000	0.044	0.025	0.000	0.044
12.5	393	2.20	471.6	3.37	0.000	0.053	0.000	0.000	0.020
14.5	231	1.93	554.4	7.48	0.000	0.035	0.048	0.000	0.000
16	361	2.33	868.8	3.81	0.000	0.044	0.025	0.000	0.044
20.5	586	1.97	703.2	1.85	0.000	0.073	0.041	0.000	0.041
25	190	1.73	456	10.02	0.000	0.063	0.047	0.000	0.000
31	383	2.18	919.2	3.50	0.000	0.029	0.091	0.000	0.042
34	345	1.96	416.4	4.06	0.000	0.046	0.049	0.000	0.041
40	288	1.89	138.24	5.37	0.000	0.035	0.000	0.000	0.031
46.5	213	1.71	255.6	8.45	0.000	0.061	0.061	0.000	0.000
50	223	1.74	89.2	7.88	0.000	0.242	0.072	0.000	0.000
55	247	1.95	144.6	7.02	0.000	0.069	0.053	0.000	0.000
60	324	1.91	768	4.59	0.000	0.096	0.000	0.000	0.000
62	223	1.93	535.2	7.88	0.000	0.063	0.211	0.000	0.000
65	397	1.92	950.4	3.33	0.030	0.149	0.244	0.000	0.000
67	378	1.89	904.8	3.59	0.032	0.156	0.122	0.000	0.024
70	620	2.37	1488	1.70	0.000	0.065	0.185	0.018	0.015
72.5	539	2.48	1288.8	2.11	0.000	0.141	0.096	0.000	0.028
75	445	2.47	1065.6	2.81	0.000	0.079	0.094	0.000	0.029
80	837	2.42	1051.2	1.01	0.017	0.151	0.146	0.000	0.038
85	516	2.51	1238.4	2.24	0.035	0.112	0.066	0.017	0.033
90	601	2.36	1442.4	1.78	0.013	0.097	0.088	0.000	0.000

Table E.2.2 (cont.)

Depth (cm)	CyK	DiAc	DiAcC	DiAcW	DiAs	DiE	DiGa	DiGm	DiGo
0	0.000	0.055	0.000	0.000	0.000	0.074	0.022	0.000	0.288
0.5	0.000	0.139	0.000	0.000	0.000	0.064	0.000	0.000	0.346
1	0.000	0.094	0.000	0.000	0.000	0.038	0.032	0.035	0.391
1.5	0.000	0.106	0.000	0.000	0.000	0.050	0.028	0.025	0.388
2	0.000	0.106	0.000	0.000	0.000	0.049	0.030	0.049	0.292
2.5	0.000	0.147	0.000	0.000	0.000	0.023	0.087	0.000	0.318
3	0.000	0.111	0.000	0.000	0.000	0.024	0.000	0.027	0.339
3.5	0.000	0.085	0.000	0.000	0.000	0.071	0.217	0.000	0.306
4	0.000	0.052	0.047	0.000	0.000	0.032	0.035	0.078	0.253
4.5	0.000	0.125	0.000	0.000	0.000	0.073	0.152	0.000	0.377
5	0.000	0.087	0.000	0.000	0.000	0.059	0.046	0.064	0.388
5.5	0.000	0.068	0.000	0.000	0.000	0.039	0.180	0.000	0.332
6	0.000	0.086	0.000	0.000	0.000	0.039	0.062	0.062	0.300
6.5	0.000	0.119	0.000	0.000	0.000	0.045	0.138	0.039	0.322
7	0.000	0.100	0.000	0.000	0.000	0.000	0.061	0.061	0.367
7.5	0.000	0.063	0.000	0.000	0.039	0.044	0.088	0.054	0.229
8	0.000	0.074	0.000	0.000	0.000	0.056	0.108	0.082	0.199
8.5	0.000	0.060	0.000	0.000	0.033	0.039	0.098	0.086	0.307
9	0.000	0.064	0.000	0.000	0.047	0.000	0.090	0.000	0.405
9.5	0.000	0.033	0.000	0.000	0.083	0.030	0.067	0.137	0.287
10	0.000	0.079	0.000	0.000	0.000	0.000	0.050	0.085	0.312
11.5	0.000	0.080	0.028	0.000	0.000	0.050	0.036	0.080	0.268
12.5	0.000	0.059	0.000	0.000	0.000	0.020	0.038	0.153	0.249
14.5	0.000	0.134	0.000	0.000	0.000	0.074	0.095	0.000	0.264
16	0.000	0.075	0.039	0.000	0.000	0.036	0.036	0.066	0.252
20.5	0.000	0.118	0.038	0.000	0.015	0.022	0.038	0.000	0.352
25	0.000	0.100	0.000	0.000	0.105	0.058	0.047	0.000	0.337
31	0.000	0.039	0.026	0.000	0.000	0.068	0.034	0.042	0.300
34	0.000	0.104	0.000	0.000	0.038	0.061	0.038	0.032	0.319
40	0.000	0.108	0.000	0.000	0.000	0.038	0.038	0.035	0.319
46.5	0.000	0.070	0.000	0.000	0.047	0.000	0.070	0.000	0.230
50	0.036	0.054	0.000	0.000	0.000	0.000	0.081	0.000	0.148
55	0.000	0.065	0.000	0.000	0.040	0.000	0.032	0.194	0.073
60	0.000	0.031	0.068	0.000	0.000	0.000	0.046	0.114	0.080
62	0.000	0.058	0.054	0.000	0.000	0.058	0.000	0.040	0.049
65	0.000	0.023	0.000	0.000	0.000	0.086	0.000	0.000	0.035
67	0.000	0.045	0.000	0.000	0.000	0.079	0.000	0.000	0.048
70	0.000	0.039	0.026	0.019	0.000	0.082	0.027	0.031	0.044
72.5	0.000	0.030	0.058	0.000	0.000	0.050	0.022	0.054	0.076
75	0.000	0.061	0.038	0.000	0.038	0.052	0.052	0.083	0.029
80	0.000	0.039	0.063	0.000	0.000	0.023	0.048	0.000	0.081
85	0.000	0.048	0.037	0.000	0.000	0.029	0.021	0.048	0.023
90	0.000	0.028	0.048	0.000	0.000	0.048	0.023	0.030	0.047

Table E.2.2 (cont.)

Depth (cm)	DiGp	DiOE	DiOL	DiOO	DiOS	DiOTe	DiPr	DiSc	DiU
0	0.071	0.000	0.030	0.121	0.000	0.000	0.000	0.000	0.000
0.5	0.049	0.000	0.034	0.083	0.000	0.000	0.000	0.000	0.000
1	0.050	0.000	0.024	0.094	0.000	0.000	0.000	0.000	0.000
1.5	0.059	0.000	0.025	0.050	0.000	0.000	0.000	0.000	0.000
2	0.068	0.000	0.000	0.061	0.000	0.000	0.000	0.000	0.000
2.5	0.000	0.000	0.061	0.061	0.000	0.000	0.000	0.000	0.049
3	0.066	0.000	0.051	0.057	0.000	0.000	0.000	0.000	0.000
3.5	0.043	0.000	0.036	0.043	0.000	0.000	0.000	0.000	0.000
4	0.084	0.000	0.000	0.047	0.000	0.000	0.000	0.000	0.000
4.5	0.000	0.000	0.045	0.052	0.000	0.000	0.000	0.000	0.000
5	0.055	0.000	0.000	0.046	0.000	0.000	0.000	0.000	0.000
5.5	0.049	0.000	0.044	0.068	0.000	0.000	0.000	0.000	0.000
6	0.053	0.053	0.000	0.042	0.000	0.000	0.000	0.000	0.000
6.5	0.039	0.000	0.000	0.064	0.000	0.000	0.000	0.000	0.000
7	0.066	0.000	0.000	0.083	0.000	0.039	0.000	0.000	0.000
7.5	0.083	0.000	0.049	0.088	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.043	0.065	0.000	0.000	0.000	0.000	0.000
8.5	0.063	0.000	0.000	0.077	0.000	0.000	0.000	0.000	0.000
9	0.060	0.000	0.000	0.050	0.000	0.000	0.000	0.000	0.000
9.5	0.063	0.000	0.000	0.067	0.000	0.000	0.000	0.000	0.000
10	0.069	0.000	0.000	0.085	0.000	0.000	0.000	0.000	0.000
11.5	0.077	0.033	0.000	0.050	0.000	0.000	0.000	0.000	0.000
12.5	0.051	0.000	0.020	0.056	0.000	0.028	0.000	0.031	0.000
14.5	0.069	0.000	0.039	0.052	0.000	0.000	0.000	0.000	0.000
16	0.047	0.000	0.022	0.061	0.000	0.000	0.000	0.025	0.000
20.5	0.000	0.000	0.017	0.077	0.000	0.000	0.000	0.000	0.000
25	0.042	0.000	0.000	0.042	0.000	0.000	0.000	0.000	0.000
31	0.068	0.000	0.044	0.084	0.000	0.021	0.000	0.000	0.000
34	0.070	0.000	0.000	0.096	0.000	0.000	0.000	0.000	0.000
40	0.063	0.000	0.000	0.083	0.000	0.028	0.000	0.000	0.000
46.5	0.094	0.000	0.000	0.155	0.000	0.000	0.000	0.000	0.000
50	0.036	0.000	0.000	0.085	0.000	0.000	0.000	0.000	0.000
55	0.057	0.000	0.000	0.117	0.000	0.000	0.000	0.000	0.000
60	0.120	0.000	0.000	0.108	0.000	0.000	0.000	0.000	0.000
62	0.148	0.000	0.000	0.117	0.000	0.000	0.000	0.000	0.000
65	0.131	0.000	0.000	0.065	0.000	0.000	0.000	0.000	0.000
67	0.193	0.000	0.000	0.103	0.000	0.000	0.000	0.000	0.000
70	0.190	0.024	0.000	0.077	0.000	0.000	0.016	0.000	0.000
72.5	0.132	0.037	0.000	0.089	0.000	0.028	0.000	0.000	0.019
75	0.088	0.000	0.000	0.146	0.000	0.029	0.020	0.000	0.000
80	0.000	0.000	0.000	0.204	0.019	0.019	0.000	0.000	0.023
85	0.079	0.000	0.000	0.192	0.019	0.025	0.058	0.000	0.000
90	0.057	0.000	0.000	0.246	0.000	0.030	0.060	0.000	0.015

Table E.2.2 (cont.)

Depth (cm)	LaV	LeS	PoC	Sp7
0	0.000	0.000	0.000	0.052
0.5	0.000	0.000	0.000	0.034
1	0.000	0.000	0.000	0.000
1.5	0.000	0.000	0.000	0.069
2	0.000	0.000	0.000	0.068
2.5	0.000	0.000	0.000	0.069
3	0.000	0.000	0.000	0.102
3.5	0.000	0.000	0.000	0.000
4	0.000	0.000	0.026	0.169
4.5	0.000	0.000	0.000	0.000
5	0.000	0.000	0.055	0.000
5.5	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.047
6.5	0.000	0.000	0.000	0.000
7	0.000	0.000	0.039	0.000
7.5	0.000	0.000	0.000	0.000
8	0.000	0.000	0.048	0.056
8.5	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000
9.5	0.000	0.000	0.047	0.000
10	0.000	0.000	0.000	0.041
11.5	0.000	0.000	0.041	0.058
12.5	0.000	0.000	0.130	0.028
14.5	0.000	0.000	0.000	0.056
16	0.000	0.000	0.069	0.078
20.5	0.000	0.000	0.000	0.102
25	0.000	0.000	0.000	0.000
31	0.000	0.000	0.031	0.000
34	0.000	0.000	0.000	0.000
40	0.000	0.000	0.031	0.031
46.5	0.000	0.000	0.000	0.000
50	0.000	0.000	0.036	0.000
55	0.000	0.000	0.130	0.000
60	0.000	0.000	0.173	0.000
62	0.000	0.000	0.040	0.000
65	0.000	0.000	0.035	0.088
67	0.000	0.000	0.000	0.029
70	0.000	0.000	0.045	0.026
72.5	0.000	0.000	0.039	0.035
75	0.000	0.018	0.054	0.000
80	0.026	0.011	0.032	0.030
85	0.025	0.000	0.050	0.000
90	0.000	0.013	0.040	0.030

Table E.2.3 - Principal component analysis (PCA) species loadings from PCA-B
(excludes DiGO). See caption of Table 2 for species acronyms.

	PC1-B	PC2-B	PC3-B	PC4-B
DiOO	-0.177	-0.074	0.166	-0.173
CeCA	-0.090	-0.321	0.170	0.239
CeAD	-0.334	-0.242	-0.052	-0.262
DiGa	0.581	0.178	0.235	-0.092
DiGm	-0.196	0.571	-0.067	0.123
SmGo	-0.231	-0.040	0.066	0.336
PoC	-0.266	0.364	-0.002	-0.058
Sp7	-0.014	-0.073	-0.554	0.006
DiAc	0.411	-0.024	-0.264	0.028
DiAs	0.038	0.040	0.144	0.007
DiE	0.101	-0.106	-0.033	0.198
DiAcC	-0.152	0.010	-0.034	-0.054
DiOL	0.166	-0.038	-0.073	-0.002
DiPr	-0.053	-0.014	0.034	-0.039
DiOE	-0.020	0.012	-0.034	0.037
DiU	0.008	-0.021	-0.018	-0.050
CuT	-0.038	0.059	-0.037	0.025
DiOTe	-0.050	0.034	0.025	-0.025
CyK	-0.007	-0.010	0.006	-0.028
CeAA	-0.046	-0.047	0.015	-0.013
DiSc	-0.014	0.039	-0.023	-0.009
LaV	-0.017	-0.010	0.011	-0.026
DiOS	-0.012	-0.007	0.008	-0.019
DiAcW	-0.005	-0.004	0.003	0.011
LeS	-0.012	-0.003	0.010	-0.013
CeCS	-0.012	-0.005	0.007	0.003

Table E.2.4 – (on the following page) Principal component analysis (PCA) subsample loadings from PCA-B (excludes DiGO).

Depth (cm)	PC1-B	PC2-B	PC3-B	PC4-B
-68.4	-0.129	-0.434	-0.040	0.024
-34.4	0.094	-0.396	-0.219	0.200
-0.3	0.013	-0.178	0.071	-0.045
33.8	0.062	-0.264	-0.402	0.136
67.9	-0.002	-0.109	-0.375	0.179
101.9	0.444	-0.145	-0.406	-0.506
136	0.028	-0.227	-0.608	0.217
170.1	0.629	0.025	0.339	0.019
204.1	-0.135	0.184	-0.701	0.131
238.2	0.682	-0.012	0.148	-0.119
272.3	0.103	0.340	0.042	0.412
293.4	0.572	0.041	0.374	-0.091
314.6	0.113	0.108	-0.263	0.145
335.7	0.492	0.091	0.223	0.106
356.9	0.094	0.267	0.164	0.147
378	0.206	0.104	0.312	0.340
399.1	0.248	0.310	-0.148	-0.204
420.3	0.120	0.221	0.306	0.155
441.4	0.262	-0.088	0.360	-0.092
462.6	-0.118	0.518	0.296	0.193
483.7	-0.038	0.189	-0.114	0.062
570.2	-0.113	0.293	-0.370	0.204
627.8	-0.253	0.748	-0.180	-0.157
743.1	0.412	-0.163	-0.230	0.119
808.1	-0.119	0.314	-0.462	-0.095
973.3	0.134	-0.240	-0.561	-0.492
1154.2	0.207	-0.200	0.151	-0.042
1410.8	-0.126	-0.033	0.215	0.320
1573.2	0.063	-0.084	0.099	0.113
2004.5	0.065	0.166	-0.237	-0.111
2469.8	-0.012	-0.196	0.381	-0.232
2805.4	-0.187	-0.271	0.171	-0.784
3239	-0.330	0.614	0.103	-0.147
3598.6	-0.446	0.532	0.108	-0.296
3892	-0.335	-0.260	0.252	0.462
4332	-0.350	-0.493	-0.015	0.320
4601.8	-0.362	-0.446	0.085	0.248
5006.4	-0.290	-0.234	0.190	0.618
5253.3	-0.439	-0.134	0.026	0.049
5500.2	-0.253	0.100	0.273	-0.031
5833.5	-0.263	-0.332	0.200	-0.644
6167	-0.390	-0.058	0.229	-0.392
6622.2	-0.353	-0.169	0.214	-0.440

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