u Ottawa

L'Université canadienne
Canada's university

FACULTÉ DES ÉTUDES SUPÉRIEURES ET POSTOCTORALES

uOttawa

L'Université canadienne
Canada's university

FACULTY OF GRADUATE AND POSDOCTORAL STUDIES

Susan Zabenskie
AUTEUR DE LA THÈSE / AUTHOR OF THESIS

M.Sc. (Geography)
GRADE / DEGREE

Department of Geography
FACULTÉ, ÉCOLE, DÉPARTEMENT / FACULTY, SCHOOL, DEPARTMENT

Post-Glacial Climatic Change on Boothia Peninsula, Nunavut, Canada

TITRE DE LA THÈSE / TITLE OF THESIS

Konrad Gajewski
DIRECTEUR (DIRECTRICE) DE LA THÈSE / THESIS SUPERVISOR

CO-DIRECTEUR (CO-DIRECTRICE) DE LA THÈSE / THESIS CO-SUPERVISOR

EXAMINATEURS (EXAMINATRICES) DE LA THÈSE / THESIS EXAMINERS

Bernard Lauriol

Mike Sawada

Gary W. Slater
Le Doyen de la Faculté des études supérieures et postdoctorales / Dean of the Faculty of Graduate and Postdoctoral Studies

POST-GLACIAL CLIMATIC CHANGE ON BOOTHIA PENINSULA, NUNAVUT, CANADA

SUSAN ZABENSKIE

THESIS SUBMITTED TO THE
FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE MSc IN THE DEPARTMENT OF GEOGRAPHY

DEPARTMENT OF GEOGRAPHY
FACULTY OF ARTS
UNIVERSITY OF OTTAWA

Your file Votre référence
ISBN: 978-0-494-25845-3
Our file Notre référence
ISBN: 978-0-494-25845-3

Abstract

A high temporal resolution pollen diagram from a lake in the middle-Arctic region of the Boothia Peninsula, Nunavut, Canada, documents the history of the regional vegetation and climate for the past 7200 years. A diatom sequence had been previously prepared from this core. Major tundra pollen taxa in the core include Cyperaceae and *Salix*, with Cyperaceae comprising over 50% of the pollen in the early and late Holocene. Tree pollen, transported from far to the south, comprised a large percentage of the pollen sum, with *Pinus* accounting for 30% of the pollen in some levels of the core. Pollen percentages and concentrations of taxa typical of the middle-Arctic were highest in the mid-Holocene, corresponding to warm conditions. Decreasing pollen concentrations indicate cooling temperatures, with more rapid decreases occurring around 4200, 3800-3400, and 2500 cal yr BP. Pollen percentages of *Salix*, Cyperaceae, and *Artemisia* increased in the past 35 years in response to global warming. Reconstructions of July temperature using the modern analog technique showed the mid-Holocene (5800-2800 cal yr BP) was approximately 1°C higher than during the past 1000 years.

Résumé

Une étude à haute résolution de pollen provenant de sediment pris d'un lac situé sur la péninsule Boothia dans l'Arctique canadien, fut construite dans le but de documenter l'histoire végétative et climatique de cette region au cours des derniers 7200 ans. De cette même carotte de sediment, une étude comparable basée sur les diatomées avait déjà été complétée. Dans cette region, qualifiée comme tundra, les espèces de pollen les plus abondantes en pourcentage comprenaient les Cyperaceae et les *Salix,* avec Cyperaceae représentant plus de 50% du pollen trouvé au début ainsi qu'à la fin de la carrotte. Le pollen des arbres, provenant de regions éloignées du sud, représentait un grand pourcentage du pollen total, avec *Pinus* comptant jusqu'à 30% du pollen dans plusieurs niveaux de la carrotte. Les pourcentages et concentrations des taxons charactéristiques de l'Arctique "moyen" étaient les plus hauts dans le milieu de l'Holocène, indiquant un climat plus chaud à cette période. Une baisse des concentrations des espèces de pollen autour de 4200, 3800-3400 et 2500 ans avant le present représente une baisse de la température marquée à ces dates . Les poucentages en pollen de *Salix,* Cyperaceae et *Artemisia* ont augmenté pendant les derniers 35 ans en réponse au rechauffement planétaire. Une reconstruction de la temperature moyenne du mois juillet basée sur la technique de l'analogue modern (Modern Analog Technique) a sut démontrer que les températures au cours du milieu de l'Holocène étaient en moyenne 1°C plus élévées que les températures des 1000 dernières années.

Acknowledgements

It has been an incredible road to the final stage of this thesis. I would first like to thank my supervisor Dr. Konrad Gajewski. I could never have done so much in such a short period of time without the 'encouragement' from Konrad, "Just do it".

I would like to also thank my committee members, Dr. Mike Sawada, Dr. Bernard Lauriol and Presidents Dr. Brian Ray and Dr. Roger Needham for their advice and support during the two years of my thesis.

Thank you to the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), the National Sciences and Engineering Research Council (NSERC), the Northern Scientific Training Program (NSTP) and the Polar Continental Shelf Project (PCSP) for without the support of these organizations my thesis would not have been possible.

I would also like to thank my friends for being there through those hard times. To my new friends and my friends from back home, I appreciated all your advice, help and love throughout this time.

Thanks to everyone in the LPC, here and far away for welcoming me when I arrived. Thank you for your willingness to help and answer questions. Your support and advice has been invaluable.

Lastly, I want to thank my family for their constant encouragement throughout my thesis. They were always there with love, support, encouragement and always had faith in me.

Table of Contents

List of Figures

List of Tables

CHAPTER 1 - INTRODUCTION AND SITE DESCRIPTION

Introduction

The earth's climate is changing and the Canadian Arctic, in particular, is already feeling the impacts of global warming (e.g., Overpeck et al 1997). However, predictions of future climate change impacts on the biosphere are difficult because of the complex response of ecosystems to climate variations. One source of information about possible future impacts is the study of the past. By analyzing how Arctic ecosystems were impacted by past climate changes, we can better infer possible future impacts.

Instrumental climate records of the Canadian Arctic are lacking prior to the 1950's, therefore, we must use proxy records to determine past climate changes. A major proxy indicator of past climates is the pollen produced by plants, some of which are deposited in lake sediments. Because pollen assemblages are related to the vegetation, which, in turn, is related to the climate (Bennett and Willis 2001) pollen diagrams prepared from lake sediment cores document the history of the regional vegetation through time. Climate changes occur on a regional basis and we would expect changes in pollen to occur on large scales.

Pollen are an ideal proxy-climate indicator because they provide a record of the long–term environmental response to climate through time. The modern pollen assemblages can be related to the modern climate and these relations, in turn, can be used to estimate past climates using various numerical analyses, such as the modern analog technique (MAT) (Gajewski 2002).

At present, pollen diagrams have been prepared from only several regions of the Canadian Arctic and Greenland (Gajewski and Atkinson 2003). Many pollen records have been prepared from Greenland including diagrams from Amdrup (Bay and Fredskild 1997), KlaresØ (Fredskild 1973), and BasaltsØ (Wagner et al 2000), among many others. Pollen records from Arctic Canada include sites from Ellesmere Island (Hyvarinen 1985), Prince of Wales Island (Gajewski and Frappier 1995), low Arctic Nunavut (Seppa et al 2003), Banks Island (Gajewski et al 2000) and Somerset Island (Gajewski 1995). Several pollen diagrams are available from Baffin Island as well, including Windy Lake, (Andrews 1979), Baffin Island (Short et al 1989) and Fog Lake (Wolfe et al 2000). Modern samples for use in calibration are available from Banks (Ritchie et al 1987), Somerset (Gajewski 1995), Ellesmere (Gajewski et al 1995) and Baffin Island (Kerwin 2004), as well as a set of samples from central and eastern Arctic islands (Gajewski 2002).

Although these studies have provided qualitative estimates of the climates of the Arctic during the Holocene, there still remain questions about the postglacial climates of the region (Gajewski and Atkinson 2003). To describe in some detail the climate changes in the region, several deficiencies must be overcome, including a low density of sites, a low temporal resolution of the existing pollen diagrams and problems with radiocarbon dating of the cores (Gajewski et al 1995; Gajewski and Atkinson 2003; Bigelow et al 2003; Kauffman et al 2004).

This study will contribute to the knowledge of the postglacial climate and vegetation history of the Canadian Arctic. A pollen diagram was prepared from Lake JR01 on Boothia Peninsula. The diagram was prepared at a higher temporal resolution

than previously-published studies. Sediment analysis (including sediment loss-on-ignition LOI, magnetic susceptibility) was also performed at high resolution. The analysis of the pollen assemblages from this core, along with the quantitative estimation of the past climate will be a step toward the goal of providing a network of sites in the Arctic islands that document the Holocene climatic history.

Site Description

The study site, Lake JR01 (69°54'N, 95°4.2'W, 120 m.a.s.l.) is located in the southwestern region of Boothia Peninsula. The bedrock consists of Precambrian Shield. Boothia Peninsula is a plateau with low, rolling hills characterized by thick glacial deposits and little relief (Dyke 1984). The lake is in the middle-Arctic vegetation zone near the transition to the low-Arctic. The region has continuous herbaceous cover dominated by *Dryas, Salix* and S*axifraga* tundra (Bliss 1988). Climate data from nearby Pelly Bay, Taloyoak and Shepherd Bay indicate cold, dry winters and short, cool damp summers (Canada Atmospheric Service 1975, from Dyke 1984). The lake is closest to the community of Taloyoak (location: 69°32'N, 93°31'W), which has a mean annual temperature and precipitation of -15.4°C and 153.4 mm respectively and mean July temperature of 7.1°C (Canada Atmospheric Service 1975, from Dyke 1984). In the winter, dominant winds are from the south; winds are northeast in spring and summer and northwesterly in the fall (Maxwell 1982). Lake JR01 is approximately 700 by 350 metres in size with two small stream inputs that enter the lake via sedge meadows (LeBlanc 2004). It is a typical oligotrophic lake with pH of 8.10 and water conductivity of 220 μScm^{-1} (LeBlanc 2004).

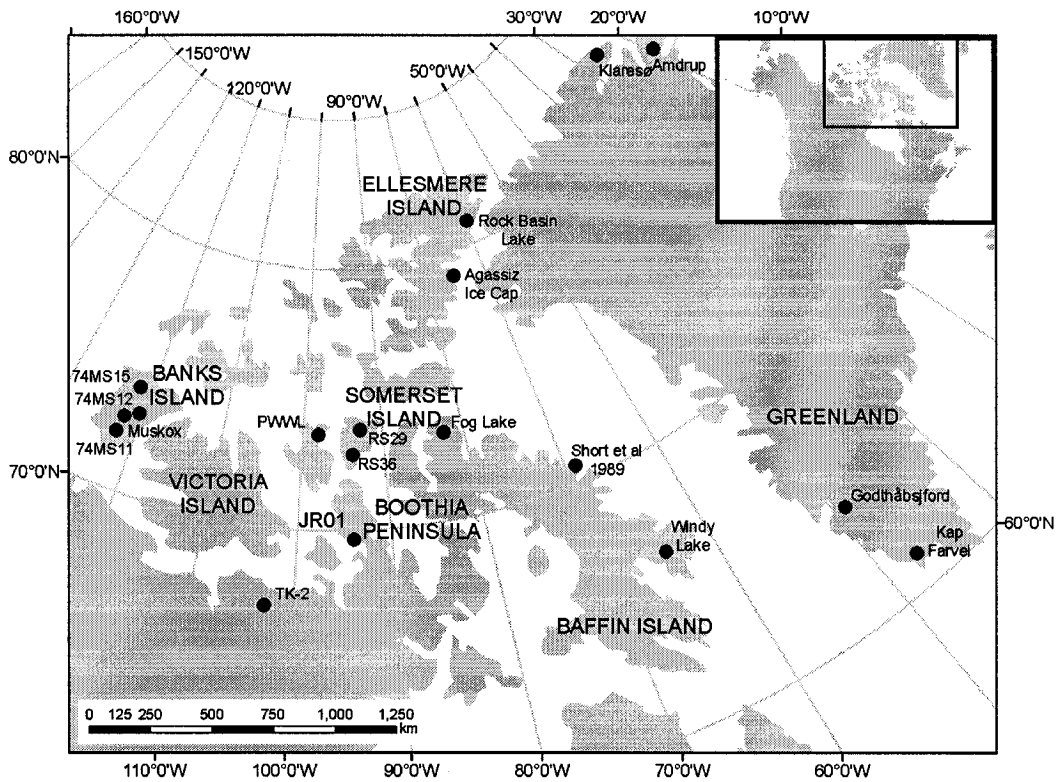

Figure 1: Map of pollen studies in the Canadian Arctic and Greenland.

CHAPTER 2 – LITERATURE REVIEW

Pollen Analysis

Pollen grains are produced by angiosperms and gymnosperms. Other vascular plants such as pteridophytes, as well as some mosses, produce spores that can also be identified in pollen preparations. Pollen is produced in the anthers of plants and is dispersed by wind, insects or other animal vectors. Most plants that have their pollen dispersed by wind tend to produce large amounts of pollen (Bennett and Willis 2001), but only a miniscule fraction of the pollen is used for reproduction. The remainder is emitted into the atmosphere and eventually falls to the ground, entering lakes, rivers or the sea.

The walls of the pollen grains are made of cellulose and a substance "sporopollenin" (Bennett and Willis 2001). Sporopollenin allows pollen grains to be preserved indefinitely in an anaerobic environment (e.g., lake sediments) because it is resistant to most chemicals and physical degradation, except oxidation. The resistance of the sporopollenin is the key factor enabling the use of pollen as a fossil; pollen grains are among the most resistant substances in nature. Indeed, the procedure used in the laboratory for pollen analysis involves the use of strong acids and bases to remove all other components of the sample, leaving the pollen grains (Bennett and Willis 2001). Pollen grains can be identified using the shape of the grain and form of the sculpture of the outer walls of the grains. Identification is aided by comparing the fossil pollen to known reference material prepared from living plants.

The pollen grains extracted from sediment samples are related to the surrounding vegetation, although not necessarily in a simple fashion. In turn, the pollen assemblages and vegetation are associated with the ecological and climatic conditions (Birks and Birks 1980). This enables pollen from lake sediments to be an indirect proxy to determine past environmental change on land.

Pollen from dated sediments provide an index of vegetation that existed during that time period. By using multiple pollen samples, vegetation changes through a period of time and space may be shown (Bennett and Willis 2001).

Arctic Pollen Analysis

In the Canadian Arctic, as in any location, there are limits to the use of pollen analysis that must be considered when interpreting pollen diagrams. Problems that have been identified include long-distance transport, low pollen concentrations, contamination by fossils from older deposits and dating of the sediments.

A certain amount of the pollen deposited in lake sediments originates from immediately around the lake (local pollen); whereas, a large portion of the pollen comes from a larger area (regional component) (Birks and Birks 1980). A third component of the pollen rain at any site originates from long-distance transport of pollen grains. In the case of the Arctic, long-distance pollen grains originate in forested regions to the south. This creates a problem if the main goal of the study is to reconstruct local or regional vegetation, because of the small amount of local pollen deposition. However, the long-distance component may, in principle, be used to interpret past air mass trajectories (Bourgeois et al 2000, Barry et al 1981). There are currently too few studies from the Arctic to be able to interpret regional pollen transport (Gajewski et al 1995).

Pollen concentrations found in lake sediments are often low. Concentrations in Arctic sediments can be as few as 1000 grains/cm^3 (Gajewski et al 1995); typical concentrations in temperate regions, for example, are orders of magnitude higher. This makes pollen studies at many sites difficult due to the amount of time needed to count sufficient pollen grains. Frequently, there may be as few as 20-50 grains on a slide (Gajewski et al 1995). Normal pollen sums are over 500 grains and because it takes many hours to count one slide; it would be impossible to obtain pollen from many sites in a reasonable time (Gajewski et al 1995). To obtain a large enough count, larger sediment samples are needed to obtain sufficient pollen.

Contamination of fossils by older deposits is a problem in some regions of the Arctic. The problem arises because several areas are underlain by Tertiary sediments, which may be eroding, and thereby, contributing pollen to the Holocene deposits (Hodgson 1985). Because some palynomorphs from the Tertiary era are different from modern types, this contamination by pollen grains from older deposits has been identified (Gajewski et al 1995). However, the Tertiary palynomorphs may also include taxa that exist today; therefore, the extent of the contamination may be difficult to assess (Gajewski 1995).

Difficulties in dating Arctic lake sediments arise from the lack of organic material available for dating. Organic material is used for radiocarbon dates but often this material is lacking, or in such low quantities that obtaining dates is not feasible.

When conducting pollen analysis in the Canadian Arctic there are certain conditions that must be taken into consideration before a specific lake is sampled. Lake depth must exceed approximately three metres to avoid freezing and mixing of the

bottom sediment (Nichols 1967). Thermokarst lakes must be avoided due to potential disturbances. Lakes chosen should be small with a minimum amount of water throughflow. Preferably, the sediment accumulation should be as great as possible to enable the temporal resolution of the resulting pollen diagram to be as great as possible.

Topography plays an important role in the climate of the Canadian Arctic. Labrador, Baffin, Devon, Ellesmere and Axel Heiberg Islands are characterized by a mountain range running in the north-south direction. This mountain range acts as a barrier to air-flow (Porsild 1964). This topography affects the climatic conditions on either side of the mountain chain, with an increased temperature and precipitation toward the east side (Porsild 1964). This in turn influences plant abundance and diversity on that landscape. The mountain range is split in two locations, separating Ungava-Labrador from Baffin Island and Lancaster Sound from Devon Island (Porsild 1955).

Bedrock has an effect on nutrients and therefore plant production, further affecting the pollen assemblages in the lake sediments of the region. The high-Arctic is generally underlain by Tertiary deposits, including coal seams that contain pollen and spores of plants that grew in this region (Gajewski 2002). Much of the middle-Arctic is underlain by carbonates that are nutrient poor and support a more impoverished flora (Gajewski 2002). Parts of the low-Arctic are underlain by rocks of the Canadian Shield (Gajewski 2002).

Pollen assemblages reflect the vegetation and differ between three major vegetation regions (high-Arctic, middle-Arctic and low-Arctic) of the Canadian Arctic (Gajewski 2002). The abundance of various plant species varies from region to region.

There is a reduction in plant cover and height and woody and vascular plant species from the low to high-Arctic (Bliss 1988). These vegetation differences depend on the different climates, topography and geology of the regions. For example, the least diverse region of the Canadian Arctic is the northwest corner due to the monotonous topography and cold, dry climate in these regions. In the eastern Arctic, the mountainous topography allows for a more diverse habitat (Porsild 1964). Changes in productivity and diversity determine the vegetation zonation of the Arctic. In addition, the pollen concentrations of lake surface sediments differ across the boundary from the high to middle-Arctic (Gajewski 1995).

Fossil Pollen Studies in the Canadian Arctic

Most pollen studies from the Canadian Arctic and Greenland involve the use of lake sediment and ice cores to reconstruct climatic histories of the region. To interpret fossil pollen assemblages requires an understanding of the relation between pollen deposited in lake sediments and the surrounding vegetation and the climate. The reconstruction process involves collecting the uppermost sediment from a series of lake cores and comparing it to the surrounding vegetation and climate conditions. Modern analogs or transfer functions are determined from these modern pollen assemblages. Fossil pollen assemblages are then compared to surface assemblages to determine past climates (Gajewski et al 1995) if the analog method is used, or a functional relation between climate and pollen assemblages can be solved using fossil assemblages to estimate paleoclimate parameters.

Several studies have produced postglacial pollen sequences from the Canadian Arctic. Gajewski and Frappier (2001) analyzed a core from Prince of Wales Island.

They found low pollen concentrations in the basal sediments corresponding with low organic matter, high carbonates and higher silt amounts. Pollen concentrations increased before 6500 yr BP, especially those of *Dryas* and Cyperaceae, coinciding with a clay content increase. Poaceae and *Papaver* were higher before 6500 yr BP indicating cooler conditions than interpreted from a core from Somerset Island (Gajewski 1995). Pollen concentrations, particularly of Cyperaceae, then decreased after 4000 yr BP. Interpretations of modern pollen data show that pollen concentrations decrease to the north with cooler temperatures (Gajewski 1995). At the same time, Poaceae, *Saxifraga oppositifolia,* Brassicaceae and Ranunculaceae pollen concentrations increased (Gajewski and Frappier 2001). These changes were interpreted as a cooling of the region, as these tend to be high-Arctic plant taxa. Cyperaceae and *Saxifraga* decreased between 5000 and 3500 yr BP while *S. oppositifolia,* Brassicaceae and Polypodiaceae increased (Gajewski and Frappier 2001). Long-distance transport of *Betula* decreased over a long period of time while pollen from the low Arctic tundra and forests to the south were constant through the time period.

Pollen assemblages from two lake sediment cores from Somerset Island were studied to determine Holocene climates of this region. This area is in the transition zone between the high-Arctic and middle-Arctic; one of the sites (RS29) is located in the high-Arctic and the other (RS36) in the middle-Arctic. Both cores were very inorganic and had little variation in carbonate content (Gajewski 1995). Both showed a decrease in pollen concentration during the past 6000 yr BP with the pollen concentration at RS36 two to three times higher than before 6000 yr BP and in modern samples (Gajewski 1995). Both sites indicated that the pollen accumulation rates and

concentrations were highest in the middle-Holocene with maximum levels between 5000 and 6000 yr BP (Gajewski 1995).

The pollen assemblages from Lake RS29 showed few changes during the last 10000 yr BP. The major pollen taxa found in the core included *Oxyria digyna,* Cyperaceae, Poaceae, S*alix, Cassiope* and other Ericaceae. *Salix* increased in relative abundance in the early part of the core. Interestingly, nearly 50% of the pollen identified in the core was from the forested regions to the south, mainly *Betula, Alnus crispa, Pinus* and *Picea.*

The pollen diagram of Lake RS36, located in the middle-Arctic of Somerset Island, showed a peak of S*alix* at the expense of Cyperaceae and O. *digyna* in the oldest sediments (Gajewski 1995). Cyperaceae, *S. oppositifolia*, and Rosaceae were more abundant in this core with Ericaceae pollen being less abundant. Nearly 60% of the pollen found in Lake RS29 was local pollen as opposed to 50% in core RS36 (Gajewski 1995).

These pollen diagrams therefore indicated cooler summers in the late Holocene (Gajewski 1995). One important factor aiding in the interpretation of pollen changes is changes in the pollen concentration, which are interpreted as changes in the density of the vegetation, although the composition of the vegetation apparently changed little.

A 198 cm core was obtained from TK-2 (unofficial name) in the low-Arctic in Nunavut, Canada (Seppa et al 2003). The first of the four pollen zones, the early Holocene tundra, was from 9100-8700 cal yr BP. This zone was characterized by 25-35% *Betula* pollen. Percentages of *Salix* were greater than 10%; they then decreased at the same time that Ericaceae and *Emetrum* increased (Seppa et al 2003). Organic matter

content was low, less than 5%. Long-distance transport of *Picea* percentages comprised 5-15% of the pollen in this zone (Seppa et al 2003).

During zone 2, from 8700 to 6800 cal yr BP, percentages of *Betula* increased sharply from 37% to over 80%. This was followed by a sharp decrease in *Betula* percentages to 20% during 8100-7900 cal yr. BP when Ericaceae, Cyperaceae, and Poaceae pollen percentages increased (Seppa et al 2003).

In Zone 3, from 6800 to 4600 cal yr BP, percentages of *Alnus* increased from 5-7% to values of 15-20%. At the same time, organic matter content increased from less than 10% to values of 15% (Seppa et al 2003).

Zone 4, from 4600 cal yr BP to the present, was characterized by a slight decrease in *Alnus* percentages and increase in Ericaceae percentages (Seppa et al 2003). At this same time, *Betula* was still the dominant taxa in the pollen assemblages (Seppa et al 2003).

The pollen diagram from Lake TK-2 indicated discontinuous shrub tundra with shrubs and grasses important in the first pollen assemblage zone. The percentages of *Salix* and Ericaceae indicated cooler temperatures than present and middle-Arctic vegetation (Seppa et al 2003). Conditions then changed from a species-rich community towards a shrub-birch covered area, quickly followed by a decrease in the shrub-birch cover (Seppa et al 2003). Increases in *Alnus* and organic matter indicated warming in the middle-Holocene followed by a cooling as indicated by decreases in organic matter and increases in Ericaceae percentages (Seppa et al 2003).

A core from Rock Basin Lake (unofficial name), Ellesmere Island was analyzed and the base was dated to around 9000 years BP (Hyvarinen 1985). The basal sediments

lacked local pollen but did contain redeposited pollen, from Tertiary deposits in the general regions (Hyvarinen 1985). The amount of organic carbon increased in more recent sediments. The amount of local pollen accounted for 90% of the pollen sum in the organic sections of the core. The long-distance transported pollen grains included *Picea, Pinus, Betula* and *Alnus* (Hyvarinen 1985).

The pollen diagram was divided into four zones. The first zone from 9000-8000 BP was dominated by Poaceae and Cyperaceae pollen. *Oxyria* then increased in relative abundance. Other herb pollen found in this zone included Caryophyllaceae, *Papaver, Potentilla,* and Ranunculaceae (Hyvarinen 1985). This zone was interpreted as pioneer vegetation and ended with the arrival of S*alix* and Ericaceae.

The second zone was from 8000-7000 BP with *Salix* percentages increasing to approximately 60% at the expense of *Oxyria* from the base of this zone. Low percentages of Ericaceae were also present (Hyvarinen 1985). The spread of Ericaceae may have indicated the shrinking of snowbeds in the area (Hyvarinen 1985). The third zone, from 7000-3500 BP, showed an increase in Ericaceae and a decrease in *Salix. Salix* and *Oxyria* were co-dominant species with Ericaceae, while other herb pollen were found at low values (Hyvarinen 1985).

The final section was from 3500 to 0 BP. It was difficult to identify the beginning of this zone because the pollen flora was very similar to the previous one. Increases of Caryophyllaceae, *Dryas, Papaver,* Ranunculaceae, and *S. oppositifolia* occurred in this zone (Hyvarinen 1985). This zone was interpreted as a climatic deterioration based on the changes of the pollen assemblages after a long period of vegetational stability (Hyvarinen 1985). Pollen concentrations decreased to the

uppermost zone from 1500-2000 grains/cm^3 in the two basal zones, to 100-200 grains/cm^3 in the uppermost zone.

Five fiord sediment cores from eastern Baffin Island were collected and radiocarbon dated with two cores yielding good chronologies. At McBeth Fiord the percentage pollen diagram was divided into three pollen zones (Short et al 1989). The first zone, from 11500 to 8000 BP, was dominated by *Betula* at 45% with other pollen types having low percentages (Short et al 1989).

Zone two, from 8000 to approximately 4000 BP, contained maximum percentages of Cyperaceae (30-40%) (Short et al 1989). In this zone, *Betula* percentages decreased to between 5 and 20% (with a high of 36%) as Poaceae percentages became higher than Zone one (Short et al 1989). *Pinus* values reached their highest values (5-10%) during this zone while *Picea* values remained constant (Short et al 1989).

Zone three occurred from 4000 BP to the present and contained the highest values of Poaceae percentages found in the core, (15-20%). At the same time, *Betula* percentages reached their lowest values (Short et al 1989).

The second fiord, Sunneshine Fiord, was divided into two zones with the transition dated at approximately 9410 BP. The base of the core was dated at 11000 BP. The older zone contained *Betula* with percentages of 15-39% (except for a level where percentages were 2%); *Picea* and *Pinus* percentages made up 25% of the sum (Short et al 1989).

In the upper zone, *Picea* and *Pinus* only comprised 12.5% of the sum. Cyperaceae made up 25-36% of this zone; at the same time pollen percentages of *Betula* decreased (Short et al 1989).

In the lowest zones of the pollen percentage diagrams, *Betula* pollen dominated Sunneshine and McBeth Fiords. The age of these basal zones were before the time when birch tundra arrived in this area; therefore, Short et al (1989) concluded that *Betula* must have been transported to the site from long-distances. The timing of high percentages of *Betula* also coincided with the timing of the Baffinland glacial stade, when the climate produced unfavourable conditions for plant growth, allowing exotic species such as *Betula* to dominate (Short et al 1989).

A few studies have been undertaken from Baffin Island. Andrews et al (1979) conducted a pollen study on a 1.2 metre core from Windy Lake, Pangirtung Pass. The core, dating back to at least 3000 yr BP, showed increased absolute pollen of *Salix,* Poaceae, *Alnus,* and Caryophyllaceae before 2500 ^{14}C yr BP. This was followed by a decrease in pollen diversity and accumulation rates, especially between 1500 to 1000 ^{14}C yr BP (Andrews et al 1979). Conditions then improved, indicated by increases in pollen of *Salix, Alnus, Betula*, Caryophyllaceae, and Cyperaceae. Andrews et al (1979) estimated optimal conditions around 800 cal yr BP, then decreasing conditions, followed by a brief accumulation until around 650 BP where the record terminated (Andrews et al 1979).

Four lake sediment cores were collected from Banks Island, Northwest Territories and analyzed for pollen. These lakes included Muskox Lake, 74MS11, 74MS12, and 74MS15. 74MS11 is located in the low-Arctic whereas the other three are located in the middle-Arctic. The chronologies for these four lakes were problematic due to potential contamination by older organic matter; however the authors discuss possible adjustments to the ^{14}C dates using pollen stratigraphy (Gajewski et al 2000).

Each pollen diagram was divided into three distinct zones that were based on the percentages of the local and regional pollen: Zone 1, the early Holocene, Zone 2, the middle Holocene and Zone 3 the late Holocene (the last few thousand years).

High values of Poaceae, lower values of Cyperaceae (except in site 74MS11) and low values of *Betula* pollen occurred in Zone 1. Salix values were less than 10% in each of the four diagrams (Gajewski et al 2000).

In Zone 2, percentages of *Betula* and Cyperaceae increased in all lakes except in site 74MS11 where Cyperaceae decreased and site 74MS15, where *Betula* remained low. Poaceae percentages decreased in Zone 2 at all sites with the exception of Lake 74MS11. *Picea*, *Alnus* and *Pinus* percentages increased at Muskox Lake and 74MS11. At the same time, *Picea* percentages increased at 74MS12 (Gajewski et al 2000).

Poaceae pollen percentages increased in Zone 3 while at the same time Cyperaceae percentages decreased, except at Muskox Lake (Gajewski et al 2000). Pollen percentages of *Dryas* and *Oxyria* increased, during which *Betula* percentages remained low, distinguishing this third zone from the first. Zone 3 is also characterized by high percentages of *Artemisia,* except at Muskox Lake (Gajewski et al 2000).

The four cores on Banks Island showed that sedimentation initiated at 9000 BP. During the early Holocene, the three Southern lakes experienced a middle-Arctic vegetation whereas the lake to the north, 74MS15, had high-Arctic vegetation. A middle-Holocene warming occurred in all cores, followed by a deterioration during the late Holocene (Gajewski et al 2000).

Lake sediment studies on Greenland have been conducted at sites all around the island. Pollen analysis from the Kap Farvel area in Southern Greenland was summarized and divided into seven zones by Fredskild (1973).

Zone A, from 9600-9100 BP, was considered an *Oxyria* and *Koenigia* phase (Fredskild 1973). The area had recently been deglaciated and pollen production was very low. *Saxifraga,* Cyperaceae, Brassicaceae and Poaceae appeared in this zone. At this time, there were no long-distance transported pollen grains, indicating a cool, severe climate (Fredskild 1973).

Zone B, from 9100-8400 BP was an *Oxyria* and *Loiseleuria* zone (Fredskild 1973). Ericaceous dwarf-shrubs appeared, as well as *Dryas*, *Carex*, *Liguliflorae* and *Thalictrum* (Fredskild 1973). These species indicated open vegetation with snow patch areas (Fredskild 1973).

Sedum and Lycopodiaceae at 8400-7200 BP defined Zone C. Cyperaceae, Ericaceae, and *Lycopodium* dominated, and *Potentilla, Plantago*, and *Viscaria* arrived in the area (Fredskild 1973). These pollen assemblages indicate dwarf-shrub vegetation characterized by snow cover and moist conditions (Fredskild 1973).

In Zone D, *Salix* and Poaceae dominated from 7200-5300 BP. Pollen grains of *Salix* and *Juniperus* first appeared during this phase with counts of *Salix* similar to those of present. The pioneer plants disappeared and dwarf-shrub heaths dominated; other pollen taxa found in this zone include *Lycopodium, Thalictrum, Coptis* and *Huperzia* (Fredskild 1973). The climate at this time would have been warmer with constant snow-cover in the winter and dry summers, as interpreted from the absolute counts (Fredskild 1973).

Zone E, from 5300-3800 BP was marked by increases in *Empetrum,* Poaceae, *Juniperus* and *Salix* (Fredskild 1973). The changing pollen composition could most likely be attributed to a changing climate, and in particular, increasing summer temperature (Fredskild 1973).

Zone F, from 3800-2200 BP, was characterized by *Betula* and *Empetrum* pollen (Fredskild 1973). Pollen of *Rumex, Carex, Thymus* and *Streptopus* appeared in this phase (Fredskild 1973). During this phase the landscape was covered in dwarf-shrub heaths, indicating a warm, dry climate.

The last zone, from 2200 BP to present, was characterized by *Empetrum* and *B. glandulosa* (Fredskild 1973). *Juniperus* pollen decreased, as species that were rare in the previous zone, such as *S. oppositifolia* and *Botrychium*, increased in abundance (Fredskild 1973). These changes were most likely brought about by increased humid conditions.

In West Greenland, pollen studies were undertaken in the Godthåbsfjord area. The fossil terrestrial vegetation was summarized into five zones. Zone A, from approximately 8700-8000 BP was dominated by Poaceae, Cyperaceae, *Plantago, Empetrum* and other Ericales (Fredskild 1973). This vegetation is similar to that presently in the area.

Zone B, was characterized by Cyperaceae, *Salix* and *Thalictrum* and lasted from 8000-7000 BP (Fredskild 1973). Species indicative of dry soils appeared, including *Artemisia, Ruchmex* and *Campanula* (Fredskild 1973).

Zone C, during which *B. nana* and *Juniperus* dominated, occurred from 7000-4000 BP (Fredskild 1973). *Salix* was also prominent indicating that the climate conditions (warm and dry) were similar to that of today (Fredskild 1973).

In Zone D, from 4000-1900 BP, scrubs and dwarf-shrub heaths still dominated. Ericales and *Alnus* conquered areas that were previously covered with *Betula* and *Juniperus* in the previous zone (Fredskild 1973). The advance of *Alnus* indicated maximum warm temperatures.

The decrease of *Alnus* in Zone E from 1900 BP to present and the increase in Ericales indicated a cooling during this time period (Fredskild 1973). Around 650 BP, moister conditions were registered followed by the recent drying of ponds; the latter was attributed to the warming of the 20th Century (Fredskild 1973).

Studies in North Greenland were mainly concentrated in Klaresø, south of Jørgen Brønlund Fjord (82°10'N, 30°34'W) (Fredskild 1973). The pollen diagram was separated into five zones.

Zone A was characterized by Poaceae, Cyperaceae and *Oxyria* pollen. Exotic pollen was also found in Zone A, including *Alnus, Betula,* and Ericaceae. This zone was dated to before 6850 BP (Fredskild 1973).

In Zone B, *S. oppositifolia* increased, along with Poaceae, *Oxyria,* Cyperaceae, and *Potentilla.* Late in the zone, *Ranunculus* pollen increased in abundance. This zone dated from 6850 to approximately 6780 BP. The amount of exotic pollen decreased in this zone as compared to Zone A (Fredskild 1973).

Zone C began with a high increase in *Salix* and by high values of *S. oppositifolia* pollen. *Salix* increased to make up 50-60% of the total pollen, at the expense of

Saxifraga. This zone started at 6780 and ended at 5870 BP (Fredskild 1973). The other pollen taxa (*Dryas, Oxyria,* Cyperaceae, Poaceae, *Ranunculus,* Brassicaceae) in this diagram tended to have similar frequencies as in previous zones.

Zone D was the *Salix* zone, where it continued to be the dominant pollen in the sediment, comprising 50-60% of the total pollen grains (Fredskild 1973). Late in Zone D, the total pollen concentration decreased while the composition of the pollen stayed the same. This zone continued from 5870-4090 BP. The change from this zone to Zone E was defined by a decrease in *Salix* and an increase in Cyperaceae and Poaceae pollen (Fredskild 1973).

The last zone, Zone E, (4090-2610 BP) was characterized by increases of Poaceae, Cyperaceae, *Saxifraga* and *Oxyria* (Fredskild 1973). The amount of pollen per unit of sediment (pollen input) was greatest in Zones B-D. Zone E, with a decreased pollen input, was interpreted as experiencing cooler temperatures.

In addition to studies of lake sediments, pollen may be extracted from ice cores. An ice core from the Agassiz Ice Cap was obtained by Bourgeois et al (2000). One important aspect of ice core records is that they record changes in the pollen assemblages on annual, decadal, centennial or millennial scales of resolution, depending on depth (Bourgeois et al 2000). Because there is no local pollen on the Agassiz Ice Cap, long-distance transport of pollen was used to determine past atmospheric circulation, although non-arboreal pollen could be used to interpret conditions of the regional tundra.

In the first zone, from 11500–6000 ^{14}C yr ago, *Picea* reached a maximum whereas *Alnus* was sparse or absent (Bourgeois et al 2000). *Betula* fluctuated between 4

and 26%. Poaceae, Ericaceae and Cyperaceae had high percentages until 7000 ^{14}C yr ago (Bourgeois et al 2000). Poaceae, Ericaceae, and Cyperaceae concentrations were higher before ca. 7000 yr ago as were the concentrations of the southern trees, *Picea* and *Pinus*. *Betula* was found in higher concentrations between 11500-10500 and 8200-7000 ^{14}C yr ago.

Zone II, from 6000 ca. years ago to the present, was characterized by a decrease in the southern tree percentages. *Picea* decreased to less than 10%, from values of 21% found in Zone I. *Salix* and *Oxyria* were important components of the pollen assemblages after 6000 yr ago whereas other tundra pollen grains were absent (Bourgeois et al 2000).

The dominant pollen taxon in the past 1000 years was *Pinus*, with percentages ranging from 14% (1700-1600 ca. yr BP) to 74% (1900-1850 cal yr BP). Poaceae (16%) and *Oxyria* (8%) were the dominant herbaceous pollen (Bourgeois et al 2000). Except for *Oxyria*, all of the pollen taxa (*Pinus, Picea, Alnus, Betula, Salix,* Ericaceae, Cyperaceae and Poaceae) increased in concentration between 1000 and 1200, and remained stable between 1200-1600 A.D. Pollen concentrations then increased again at 1600 A.D. and peaked between 1800 and 1850 A.D., this time with the exception of *Pinus.*

If the herb pollen are all assumed to be of regional origin, then the high concentrations of pollen indicate dense vegetation and, in turn, a warmer climate. Pollen concentrations were higher in the early Holocene, yet diversity increased in the middle-Holocene. The pollen concentrations found in this study show similarities to a study from the northwestern mainland of Canada (Ritchie et al 1983). *Picea* migrated to the

region before 10000 yr ago when *Betula* pollen decreased in relative abundance. After cal 7000 yr ago, *Alnus* became an important component of the pollen assemblages of the region. At the same time, the treeline in this region retreated south and forested zones changed to tundra (Bourgeois et al 2000). The increase in *Picea* pollen during the early Holocene may indicate an increase in wind frequency from the southwest during spring or early summer (Bourgeois et al 2000).

Pollen studies from many regions in the Canadian Arctic and Northern Greenland, both from lake sediments and ice cores, show broadly similar sequences. The middle-Holocene was warmer, with higher pollen concentrations and a high concentration of *Salix* in the cores. The climate became cooler causing a change in the composition of the vegetation, decreasing concentrations and therefore pollen assemblages.

Pollen studies from the Canadian Arctic are still few in number and more studies are needed to provide conclusive evidence of Holocene changes in the different regions. Several issues remain unresolved. The first issue is the spatial extent of the early Holocene warming and subsequent cooling. Were similar changes seen across the Arctic? Another issue is the magnitude of the changes - how much warmer was the early Holocene than today? A third issue is the timing of the climate variations. Due to problems in dating, it is not clear if these variations were synchronous across the Arctic. Finally, the impact of these changes on the vegetation is not entirely known. Although most indications suggest major climate impacts on vegetation occur through changes in density rather than composition, this remains to be demonstrated, especially in the low to middle-Arctic transition where species and functional group diversity are higher.

CHAPTER 3 - METHODS

Lake sediment cores were collected from lake JR01 (unofficial name) on Boothia Peninsula, Nunavut. Boothia Peninsula was selected in order to obtain data from the transition from middle to low-Arctic to aid in forming a network of sites across the Arctic Islands. Presently, the site is surrounded by middle-Arctic vegetation. Lake JR01 was selected because it had the properties needed for a good stratigraphic sequence. The lake is small, deep enough so as not to freeze to the bottom in winter, yet not too deep, so a sediment core could be collected using a hand-operated Livingstone corer. There is only a small inflow from a small drainage basin so much of the pollen input was expected to be aerial.

This core has been previously analyzed for diatoms by Masters student Michelle LeBlanc (LeBlanc 2002). Although loss-on-ignition (LOI) was analyzed at low resolution, more detail about the sedimentary matrix was obtained in this project.

Field Methods

Cores were collected from an ice surface with a 5 cm in diameter Livingstone corer through 5.4 metres of water. The corer was lowered to the sediment using drive rods, collecting the sediment one metre at a time. The uppermost part of the sediment (0.8 metres) was sampled in a plastic tube with piston, in order to ensure that the sediment-water interface was recovered (LeBlanc 2002). The top 20 centimetres of sediment were subsampled in the field into plastic bags at 0.5 cm increments (LeBlanc 2002). The remainder of the core was wrapped in plastic wrap and aluminum foil and stored in split black tubing at 4°C. The base of the sediment was not reached due to an

insufficient number of drive rods, nevertheless, the core did reach sediments dating to 7200 yr BP.

Dating Methodology

To compile an age-depth curve, sediment samples are dated using radiocarbon. Radiocarbon measurements of fossil organic matter are based on the decay of the isotope ^{14}C (Bjorck 2001). Carbon atoms are oxidized to form $^{14}CO_2$ (carbon dioxide), which is absorbed by living organisms. While the organism is still alive, the ^{14}C in the organism is in equilibrium with the atmosphere, assuming no fractionation. When the organism dies, uptake of $^{14}CO_2$ stops, while the decay of ^{14}C continues (Bjorck 2001) with the half-life of 5730 years. By comparing the quantity of ^{14}C decay within the organism to the amount of stable carbon in a standard sample, the years since the sample died may be estimated.

Radiocarbon dates must be converted into calendar ages since the production of ^{14}C in the atmosphere is not constant. There are two types of errors associated with the radiocarbon age curve if not calibrated. The first order error results in the ^{14}C ages being younger than the calendar years (Bartlein et al 1995). The second order error results in steps and plateaus in the radiocarbon dates, arising from short-term variations in the production of ^{14}C (Bartlein et al 1995).

^{14}C has a short half-life, therefore this method of dating can only be used to date samples from the past 40,000 years. Radiocarbon dating is also not usable for the last few decades because of measuring uncertainties arising from fossil fuel combustion (release of old CO_2) and nuclear weapon tests (increase of ^{14}C production) (Bjorck 2001).

Radiocarbon dating is dependant on organic matter, but Arctic lake sediments are commonly very inorganic. The low densities of Arctic plants on the landscape and low productivity in the water therefore make the task of radiocarbon dating more difficult.

When selecting material for radiocarbon dating, there is a hierarchy of organic material to be used: terrestrial macrofossils provide the best dates, followed by aquatic plants, aquatic animals and lastly bulk sediments (MacDonald et al 1991). Macrofossils in the lake may originate from the surrounding terrestrial environments or from the lake itself. They are thought to be transported from their original location to the lake soon after the organism has died (Bjorck 2001), but this may not always be the case. However, macrofossils are often rare in many sediment sequences. Nevertheless, terrestrial macrofossils provide the best dates.

Five dates of the sediment sequence had previously been obtained by LeBlanc (2002). Five new sections of the core were submitted for radiocarbon dating to supplement the previous dates. For each section of the core chosen to be dated, one centimetre increments, totaling up to three centimetres of sediment were subsampled. Each centimetre of sediment was placed into 50 ml plastic tubes and filled halfway with deionized water. The sediment was sieved using a 90 μm plastic screen with deionized water. Sieving was done to decrease the amount of sand and silt and make the extracting of the microfossils more efficient.

Macrofossils were then picked from the sediment to be submitted for dating. Four lines were drawn on the bottom of a plastic Petri dish to separate the dish into eight sections with a circle marked in the first section. This was done to ensure the sample was completely scanned for material. Small amounts of the sample were poured

into the Petri dish and water was added to cover the bottom. For each sediment sample, larval chironomid (non-biting midge) head capsules and other organic matter such as twigs and mosses were picked using cleaned tweezers, and placed in micro centrifuge tubes. After each centimetre was sieved, it was estimated whether the amount of organic matter was sufficient, based on previous radiocarbon samples sent for dating. If the amount was not sufficient, then another centimetre of sediment was sieved and picked. The samples were sent to Beta Analytic Inc. in Miami, Florida for analysis. The oldest date was obtained from a second sequence that had been correlated to the core used for pollen analysis by magnetic susceptibility values (LeBlanc et al 2004).

Recent sediments in the core were dated by ^{210}Pb; this had not been previously attempted on this core. ^{210}Pb dating is used to establish the sediment accumulation rate in the lakes for the past ~150 years. ^{210}Pb is a natural radioactive isotope of lead. It is formed in soils when ^{222}Rn decays and escapes to the atmosphere. The element is then precipitated out of the atmosphere via dry deposition or precipitation. This material falls into lakes, oceans and land surfaces; the ^{210}Pb falling into lakes is incorporated into the sediment (Appleby 2001). It is assumed that the sediment is continuously receiving ^{210}Pb. Using the half life of 22.3 years for ^{210}Pb, the age of sediments can be determined. Potential errors arise if, for example, there are large changes in ^{210}Pb inputs to the lake. Sometimes the sediments may be mixed by benthic organisms further making the dating less inaccurate (Appleby 2001).

During fieldwork, a glewcore (Glew 19991) was collected in the same area as the Livingstone core used for analysis. Glew corers obtain the uppermost few cm of sediment from a lake and are therefore useful for ^{210}Pb dating. The Glew core obtained

was divided into centimetre sections and placed in bags in the field, with each sample containing 12.6 cm^3. The top 20 centimetres of the Glew Core (Glew 1991) were sent to MyCore Scientific Inc. in Deep River, Ontario for ^{210}Pb analysis.

Calib501 was used to convert the radiocarbon ages to calendar year ages. Each sample was labeled and the radiocarbon age and uncertainty were entered. Once all samples had been entered, the box was closed. Under "options", "calibration" was chosen, ensuring that "sigma one" and "sigma two" were both highlighted. Calibrate was chosen from the menu at the top and the output was obtained. The mean for the "sigma two" values was used as the calibrated radiocarbon ages for this analysis (Reimer et al 2004a)

An age-depth curve for the lake sediment core of JR01 was derived by linear interpolation between the ^{210}Pb and ^{14}C dates. ^{210}Pb and calibrated calendar year ages and depths were imported into S+. Using the approximation tool, dates were interpolated for every sample as seen in Figure 3.

Other potential age-depth relations were explored. A polynomial regression of various orders was fit and residuals examined. The closest fit was using a cubic equation. However, there were large residuals in the past 150 years, as the regression line did not pass near to the ^{210}Pb ages. Given the smoothness of a polynomial equation, the regression could not be forced through the ^{210}Pb points and still fit the ^{14}C dates. The residuals had formed a pattern indicating a poor fit. A quadratic equation was also attempted and discarded because the residuals and diagnostics indicated a poor fit. Therefore, since there are not large or abrupt changes in sedimentation, the interpolated ages were considered reasonable.

Sediment Methodology

Changes in organic matter input to the sediment are determined by weight-loss-on-ignition (LOI), which is an estimate of the fraction of organic carbon and inorganic carbon (Dean 1974). The entire core was subsampled every centimetre to obtain a continuous curve of LOI. In some cases where the core had shrunk and there was less than five centimetres between each diatom sampling location (location of samples could be identified by the holes in the core), the distance was divided by five and sampled accordingly. In this way, the LOI could be related to the previously analyzed diatom data, as well as to the pollen data produced in this study.

One half cm^3 of sediment was subsampled using a spatula, measured in a calibrated sampler and placed into a previously cleaned and weighed crucible. The crucibles and sediment were weighed (wet weight). The samples were then placed into an oven at 105°C overnight (for 22.5 hours) to dry. They were then taken out of the oven and weighed again (DW_{105}). The samples were then put into a furnace at 550°C for four hours. The timing of four hours started when the furnace reached 550°C; timing did not include the amount of time it took to reach that temperature. The samples were then weighed for their dry weight at 550°C (DW_{550}). The samples were again placed in the furnace and heated to 950°C for two hours. Again the timing started once the furnace had reached 950°C. The samples were weighed one last time for their ignited weight at 950°C (DW_{950}) and recorded.

The LOI and carbonate were calculated as follows (Boyle 2001, Gajewski 2004 n.d.).

Weight percent organic matter = $100\ (DW_{105} - DW_{550})/DW_{105}$

Weight percent carbonate = $100\ (DW_{550} - DW_{905})/DW_{105}$

Magnetic susceptibility measurements were performed on the core. Magnetic susceptibility is a measure of how easily sediments are magnetized; the amount of magnetization is determined by the amount of iron within the sample. Because rocks and their weathered products contain concentrations of iron, magnetic susceptibility may be related to the mineral input to the sediment (Zolitschka et al 2001). The magnetization is related to the concentration and composition of the magnetized sediments, so magnetic susceptibility may be used to indicate changes in sedimentation rate or inputs of sediment from rainfall events.

During the measurement of magnetic susceptibility, a low magnetic field is used to induce a magnetization in the sediment. A Bartington MS2C magnetic susceptibility metre and core sensor (6 cm internal diameter) was used to measure the magnetic susceptibility of the core. The proportional factor between the magnetic field H, and the magnetization M, is the magnetic susceptibility k (M= kH; Sandgren and Snowball 2001).

Pollen Methodology

Counting and identifying pollen in Arctic sediments with low concentrations takes an inordinate amount of time, thereby limiting the resolution of the resultant pollen diagram (Gajewski et al 1995). In order to better concentrate the pollen while removing more of the sediment matrix, a method of heavy liquid separation was attempted in this study. Although used in some pollen laboratories, it had not been attempted nor implemented in studies of the post-glacial of the Canadian Arctic. I will describe the standard methods as first applied in this study, then I will describe the

heavy-liquid separation method and experiments performed to show that they did not differentially remove certain pollen taxa. Based on these experiments, it was determined that heavy liquid separation successfully removed more extraneous material from the preparation than the traditional methods and enabled counting to proceed farther. Counts obtained using both methods were combined in this study.

Samples were processed to extract the pollen according to standard methods of Faegri and Iverson (1989). Two cm^3 of sediment were subsampled every 10 centimetres in the core and placed into vials. Two cm^3 is larger than the typical amount used for pollen analysis but is necessary due to the low pollen concentrations in the Arctic. Centrifuge tubes were washed and cleaned with deionized water and dried overnight in a clean hood. Two tablets of *Lycopodium* were added to each test tube and the corresponding sample from each centrifuge vial was added. The tablets were added to the tubes in order to calculate pollen concentrations (Stockmarr 1971). The sediment was rinsed from the vials into centrifuge tubes with 10% HCl, filling the tubes ¾ full, and stirred.

After fizzing had stopped, the samples were balanced and centrifuged for five minutes at 4000 rotations per minute (rpm). A drop of ethanol was added to the top of each tube to break the surface tension and ensure the pollen did not float on the surface. After centrifuging, the samples were decanted (the HCl was poured out, making sure not to pour out the sediment) and washed. A wash consists of adding deionized water into each tube, mixing the sediment, centrifuging and decanting again. With each wash, a few drops of ethanol were added to ensure pollen did not float. Ten percent KOH was added to each of the tubes to a level of ¾ and placed in a boiling water bath for eight

minutes, stirring occasionally. The tubes were again centrifuged, decanted and another wash was performed. The samples were then poured into a 7 μm mesh sieve and sieved with sodium pyrophosphate to rid the sample of clays and silts (Cwyner et al 1979). In order to speed the process of sieving, a gloved finger was brushed along the bottom of the sieve to increase the flow of particles out of the sieve. Sieving was completed once the liquid passing through the sieve was relatively clear. After the set of samples had been sieved, they were centrifuged and decanted.

Hydrofluoric acid was then added to each tube, filling the tube half way. The tubes were placed into a boiling water bath for 15 minutes to rid the sample of the remaining silts and clays (Faegri and Iverson 1975). The tubes were then centrifuged, decanted, and washed with deionized water. Glacial acetic acid was then added to each tube (riding the tubes of water, which reacts strongly with acetolysis solution), the tubes were stirred, centrifuged and decanted. Acetolysis solution was added slowly into the tubes (in case of residual water) until they were half full and the tubes were quickly placed into a boiling water bath for three minutes (Faegri and Iverson 1975). The acetolysis solution is important as it rids the sample of much of the remaining organic material. It was imperative, once the water bath step was finished, to quickly balance the tubes with glacial acetic acid, centrifuge and decant, because the acetolysis solution has the ability to destroy pollen grains if left too long. After decanting, the tubes were filled ¾ full of glacial acetic acid, centrifuged, decanted and washed.

The centrifuge tubes were then filled ¾ full of ethanol with a drop of saffranin stain added to each tube to make identification of the pollen grains easier. The samples were centrifuged, decanted, filled with ethanol again (without the stain), centrifuged and

decanted. The tubes were filled half fill with Tertiary-butanol (TBA), stirred, centrifuged and decanted as much as possible for the next step. The sediment was poured into vials, taking care to clear the sides of sediment using TBA. Care was taken to ensure that all sediment/pollen was poured into the vials and that the vials were only ¾ full. The vials were centrifuged, decanted and a drop of silicon oil was added to each. The samples were mixed to end up with a thick, black liquid that was stored for future counting. The samples were left open for a couple of days to enable the TBA to evaporate and at this point, the labelled vials were capped and the samples were stored.

Small aliquots of the processed sediment were added to each slide and left to sit for a day to ensure that the liquid had stopped moving. Nail polish was placed on two corners of the cover slip so that the slide stayed in place and the slides were stored upright.

Pollen were counted under a microscope at 400x. The slide was scanned in transects 1mm apart to ensure the entire coverslip was counted. The pollen grains were compared to the reference material currently available in the Laboratory for Paleoclimatology and Climatology and to description in several texts (Faegri and Iverson 1975, McAndrews et al 1973, Kapp 2000). One thousand times oil immersion magnification was used for critical identification.

The total number of grains counted in pollen analysis is typically 500 grains per level. However, because the pollen concentrations in the Canadian Arctic are so low; it is difficult to obtain this sum in a reasonable time period. In general, at least 300 grains were counted for each sample given the low pollen diversity in Arctic sediments; this should still assure a sufficiently accurate estimation of the pollen percentages. Pollen

percentages were calculated by dividing each taxon by the total pollen sum (trees, shrubs, herbs and spores) for that level.

Heavy Liquid Separation of Pollen from the Sediment Matrix

We attempted to implement a heavy liquid separation, to better concentrate the pollen grains in the inorganic sediment. Heavy liquid separation is a technique used to rid samples of most, if not all the inorganic component of the sediment from the sample, in order to concentrate the pollen. Thereby, decreasing the number of slides needed to be counted. When using a heavy liquid separation, the material to be retained floats and can be decanted off, whereas the heavier material is discarded.

Although heavy liquid separation of pollen from the sediment matrix is frequently used (Bolch 1997), detailed explanations are lacking. Most protocol explanations are vague and therefore it is difficult to implement the procedure. The following protocol is based on a number of articles (Bolch 1997; Munsterman and Kerstholt 1995; Skipp and Brownfield 1993; Torresan 1987; Traverse 1988) as well as personal communication by A. Lopez and considerable experimentation.

Traditionally, bromoform has been used as a heavy liquid to increase the concentration of organisms such as conodonts in sample preparations (Bolch 1997; Munsterman and Kerstholt 1995; Savage 1988). However, bromoform is quite toxic, so today a safer chemical is used, sodium polytungstate. Sodium polytungstate is noncorrosive with a neutral pH. Although it is expensive, it can be easily reclaimed after processing a batch of samples and therefore reused as will be described below (Skipp and Brownfield 1993).

The first experiment was performed as follows. Labelled centrifuge tubes were washed and rinsed with deionized water and left to air-dry overnight in a clean fume hood.

(1) To each tube, two cm^3 of sediment was added. Two *Lycopodium* tablets were also added to allow the computation of pollen concentration. It is important not to add too much sediment.

(2) The sediment was washed from the sample vials into the centrifuge tubes using 10% HCl to a level ¾ full. The tubes were stirred and centrifuged at 4000 rpm for five minutes and decanted.

(3) Samples were washed with deionized water, centrifuged and decanted.

(4) Ten percent KOH was added, filling each tube half full and tubes were placed in a boiling water bath for eight minutes. Samples were mixed, centrifuged and decanted.

(5) Samples were washed with deionized water, centrifuged and decanted.

(6) Solution was made by mixing water with sodium polytungstate powder to obtain a density of 1.95, measured with a hydrometer. Sodium polytungstate solution was added to each tube, filling each tube ¼ full.

(7) Each tube was mixed on the vortex for five minutes. The tubes with sodium polytungstate were then centrifuged for 10 minutes at 3000 rpm.

(8) When the tubes were taken out of the centrifuge, the liquid floating on top, which included the sodium polytungstate and pollen grains, was poured into newly labelled tubes. To each tube, deionized water was added to decrease the density to one, thereby ensuring the pollen would sink upon centrifugation. A few drops of ethanol were added to further decrease the density of the liquid and to break the surface tension. All samples

were then centrifuged for 10 minutes at 3000 rpm. The liquid from some tubes were split again, adding more water to decrease the density further because pollen was still floating. After the samples were centrifuged, the decanted liquid was poured into a separate container for later cleaning. Samples that had been split were combined and all tubes were washed with water before acetolysis.

(9) Standard procedures for acetolysis, alcohol washes and mounting were followed for the remainder of the process. For the remaining steps, the samples were centrifuged at 4000 rpm for five minutes.

To recuperate the heavy liquid, the sodium polytungstate was twice filtered through an 11 μm filter to ensure all sediment particles were removed. A small pore-sized filter was used to ensure that all impurities in the liquid were extracted. The filtered sodium polytungstate was then poured into a glass flask and placed in a drying oven at 70°C to decrease the density. The liquid was kept in the oven for 43 hours, although not necessarily consecutively; it was typically dried during the day when it could be monitored. It is important to not let the polytungstate dry completely as this makes it difficult to redissolve and make new solution.

The material remaining on the filter papers were scraped and placed on slides to ensure there was not an inordinate amount lost. Upon scanning the slide, many pollen grains were found and this particular process was deemed to have not worked. Therefore, a second experiment was attempted using steps one through six as described above. However, instead of using 2 cm^3 of sediment, 1 cm^3 was used. Then, during step seven, 5 ml of sodium polytungstate was poured into each tube, instead of the arbitrary level (1/4 full) used the previous time. The samples were then blended using a vortex

mixer, centrifuged and decanted. After the solution containing the pollen had been decanted, the component containing the pollen was split into two tubes with approximately 2.5 ml of solution in each tube. The tubes were then filled with deionized water, centrifuged and the samples were combined, followed by another centrifuge. The remaining steps proceeded as above.

During the pollen processing, it appeared that pollen may have been discarded while decanting after the heavy liquid step. Therefore this process was also deemed to have not worked.

A third experiment was attempted with several added steps to ensure that a) pollen was not decanted and b) that there were few pollen remaining in the sediment after decanting. Steps one through six were performed as described above. Next, two additional washes were added at step 6 for a total of three washes after the KOH treatment. At least three washes may be necessary to rid excess particulates floating in the tubes. 10% HCL was added to the samples to acidify them before the heavy liquid process. An acidic solution may aid in the removal of non-pollen material from suspension, making it accumulate in the sediment left at the bottom of the tubes (Takeshi 1998). Sodium polytungstate (5ml) was added to each tube, vortexed, and centrifuged at a speed of 1800 rpm for 10 minutes. Samples were decanted, split and water was added. It was important to increase the speed and time of the centrifugation to 4000 rpm at five minutes at this stage to ensure that all the pollen sank to the bottom of the tubes. This time, when decanting, it was noticed that the liquid was clear and not full of pollen. The processing then continued with acetolysis after the samples were combined.

The decanted sodium polytungstate was filtered using a Buchner funnel and large filter papers, including a coffee filter to rid the liquid of large particulates. A swab from the coffee filter was taken, placed on a slide and checked for pollen; none were found. The decanted liquid was again filtered in a Buchner funnel under vacuum using a 7μm mesh. Again a swab of the mesh was examined for pollen under the microscope, and again, none were found.

At this point there were two components: the pollen that had floated in the sodium polytungstate and the sediment that was denser and sunk to the bottom of the tube. Both samples were examined for pollen. In a successful procedure, all the pollen would float in the sodium polytungstate and none would sink to the bottom. However, in reality there is always going to be some loss. If the loss is small and there is no differential loss of different taxa, the samples are usable, as the use of the *Lycopodium* "spikes" enables the computation of pollen concentration and percentages by counting only a small fraction of the total number of grains in the sediment. In order to determine if the process was successful, the amount of pollen found in the sediment had to be counted and compared with the pollen found in the supernatant to see if the proportions were the same. If the proportions of each taxon of pollen found in the sediment and in the slides prepared from the floating material were the same, then it could be deemed that the process worked.

Replicate samples were collected from four depths in the core: four samples of 2 cm^3 each and four samples of 1 cm^3 each. The four depths were chosen to obtain one sample per drive. All eight samples, to which *Lycopodium* tablets had been added, were similarly treated with, HCl, KOH, HCl and washes as described above. At this point, 5

ml of sodium polytungstate (SPT) was added to the four samples of 1 cm^3 and they were processed to the silicon oil stage. The sediment that was left after decanting the pollen was then processed using the HF method as were the 2 cm^3 samples. The samples were sieved through a 7 μm sieve with warm sodium pyrophosphate, as required by the typical protocol for Arctic lake sediment samples. Processing continued according to standard methods of Faegri and Iverson (1975).

Slides were then made from a) the SPT fraction of sediment from a depth of 193-194 cm, b) the sediment left after decanting (called the decanted fraction) and c) from the 2 cm^3 that had been treated using the traditional method (here called the HF processed). Three slides were counted from the SPT fraction, three from the decanted fraction and five from the HF processed. All 11 slides were counted, summing the counts for each process. The total pollen sum for each type of processing was determined and pollen proportions computed. The same process was also completed for another depth in the core, 338-339 cm. The second sample was processed and analysed in the same fashion as described above except only four slides were made from the HF processed slides. Results can be found in Tables 1 and 2.

Table 1: Pollen counts and proportions as a function of the total pollen sum in sediment from depth of 193-194 (cm). See text for explanation.

	SPT	Sediment	HF	SPT	Sediment	HF
	Counts			Pollen %		
Picea whole 1/1	15	2	9	3.46	1.54	4.09
Picea ½	27	7	13	6.24	5.38	5.91
Abies	2	0	0	0.46	0.00	0.00
P. diploxylon	25	1	6	5.77	0.77	2.73
Pinus undiff	27	6	12	6.24	4.62	5.45
Pinus ½	77	17	25	17.78	13.08	11.36
Betula	16	6	10	3.70	300	4.55
Populus	0	1	0	0.00	0.77	0.00
A. crispa	25	7	11	5.77	5.38	5.00
A. rugosa	0	0	0	0.00	0.00	0.00
Salix	6	3	5	1.39	2.31	2.27
Cornus	0	0	0	0.00	0.00	0.00
Cassiope	4	1	0	0.92	0.77	0.00
Caryophyllaceae	0	0	1	0.00	0.00	0.45
Chenopodiaceae	0	0	0	0.00	0.00	0.00
Compositae	3	0	3	0.69	0.00	1.36
Brassicaceae	1	0	2	0.23	0.00	0.91
Artemisia	14	8	8	3.23	6.15	3.64
Ambrosia	0	1	0	0.00	0.77	0.00
Cyperaceae	149	57	86	34.41	43.85	39.09
Poaceae	0	1	4	0.00	0.77	1.82
Oxyria	2	2	1	0.46	1.54	0.45
Plantago	0	0	1	0.00	0.00	0.45
Ranunculaceae	0	1	0	0.00	0.77	0.00
Rosaceae	1	0	0	0.23	0.00	0.00
Dryas	4	2	2	0.92	1.54	0.91
S. oppositifolia	4	1	2	0.92	0.77	0.91
Unidentifiable	7	0	3	1.62	0.00	1.36
Unknown	0	1	0	0.00	0.77	0.00
Trilete	8	1	6	1.85	0.77	2.73
Sphagnum	14	4	9	3.23	3.08	4.09
Equisetum	2	0	0	0.46	0.00	0.00
Lycopodium	0	0	1	0.00	0.00	0.45
Pediastrum	193	18	33			
"Spike"	4029	417	720			
Pollen total	433	130	220	433	130	220
Pollen/"Spike"	10.75	31.18	30.56	10.75	31.18	30.56

Table 2: As in Table 1, for sample from depth of 338-339 (cm).

	SPT	Sediment	HF	SPT	Sediment	HF
	Counts			Pollen %		
Picea 1/1	18	0	9	4.80	0.00	4.48
Picea ½	12	3	21	3.20	4.69	10.45
Abies	2	0	0	0.53	0.00	0.00
P. diploxylon	7	1	2	1.87	1.56	1.00
Pinus undiff	8	3	5	2.13	4.69	2.49
Pinus 1/2	34	5	20	9.07	7.81	9.95
Betula	21	5	19	5.60	7.81	9.45
Populus	0	0	0	0.00	0.00	0.00
A. crispa	23	5	12	6.13	7.81	5.97
A. rugosa	0	1	0	0.00	1.56	0.00
Salix	6	1	6	1.60	1.56	2.99
Cornus	1	0	0	0.27	0.00	0.00
Cassiope	0	0	1	0.00	0.00	0.50
Caryophyllaceae	0	0	0	0.00	0.00	0.00
Chenopodiaceae	5	0	0	1.33	0.00	0.00
Compositae	0	0	1	0.00	0.00	0.50
Brassicaceae	0	0	2	0.00	0.00	1.00
Artemisia	5	3	1	1.33	4.69	0.50
Ambrosia	0	1	1	0.00	1.56	0.50
Cyperaceae	200	31	86	53.33	48.44	42.79
Poaceae	4	1	2	1.07	1.56	1.00
Oxyria	0	0	2	0.00	0.00	1.00
Plantago	0	0	0	0.00	0.00	0.00
Ranunculaceae	0	0	0	0.00	0.00	0.00
Rosaceae	0	0	0	0.00	0.00	0.00
Dryas	2	0	1	0.53	0.00	0.50
S. oppositifolia	2	0	0	0.53	0.00	0.00
Unidentifiable	4	3	2	1.07	4.69	1.00
Unknown	1	0	0	0.27	0.00	0.00
Trilete	5	1	0	1.33	1.56	0.00
Sphagnum	11	0	5	2.93	0.00	2.49
Equisetum	3	0	1	0.80	0.00	0.50
Lycopodium	0	0	0	0.00	0.00	0.00
Pediastrum	201	10	33			
"Spike"	3058	623	798			
Pollen total	375	64	201	375	64	201
Pollen/"Spike"	12.26	10.27	25.19	12.26	10.27	25.19

Proportions were similar between the processes. A chi-square statistic was used to determine if the SPT method yielded similar results to the standard. The chi-square is a measure of how far the observed counts (SPT) are from the expected counts (HF-standard method) (Moore 1995):

χ^2= (observed count-expected count)^2 /expected count, with (r-1)(c-1), degrees of freedom, where r is the number of rows and c is number of columns.

The chi-square test makes certain assumptions; the expected counts must be at least one (where the expected counts are the proportions of the standard HF method) and no more than 20% of the counts have expected counts of 5 or less.

The hypothesis tested is:

- H_o: the pollen % prepared from the SPT and standard method are not statistically different.
- H_a: the SPT and standard method produce pollen assemblages that are statistically different.

Table 3: Expected and observed counts and chi-square statistic for sample from depth of 193-194 cm. "Herbs" includes *Plantago, Dryas, Oxyria,* Caryophyllaceae, Poaceae, Brassicaceae, Asteraceae, *S. oppositifolia* and unidentifiables. "Other trees and shrubs" include *Abies, Betula* and *Cassiope.* Aquatics includes trilete spores and *Sphagnum.*

Pollen	Expected (HF)	Observed (SPT)	Chi-square
Picea	9.90	9.70	0.0040
Pinus	19.30	29.00	4.87
A. crispa	5.00	5.80	0.13
Salix	2.30	1.40	0.35
Other Trees and Shrubs	5.90	6.77	0.13
Artemisia	3.60	3.20	0.04
Cyperaceae	39.00	34.00	0.64
Herbs	7.26	4.36	1.16
Aquatics	6.80	5.00	0.48
Sum	99.10	99.20	7.81

The counts were quite low, as is typical for Arctic sediments, therefore, in order to not violate the assumptions of the chi-square test, some rare pollen types were summed into categories of trees and shrubs, herbs and aquatic pollen types. Taxa that had values of zero for both the SPT and standard method were excluded from this test (Table 3).

The chi-square statistic was 7.81 with 8 degrees of freedom. This is less than the critical value at $\chi^2 = 0.25$. Therefore, we can accept H_o. If the computed chi-square value had been lower than a critical value of 0.05, we would have rejected H_o, accepted H_a and our method of using SPT would not be deemed a valid processing method.

Table 4: Expected and observed counts and chi-square statistic for pollen sample from depth of 338-339 cm. The "Aquatics and spores" category includes trilete spores, *Sphagnum* and *Equisetum*. "Herbs" includes *S. oppositifolia, Dryas, Oxyria,* Chenopodiaceae, Asteraceae, Brassicaceae, *Artemisia, Ambrosia,* unknown and unidentifiable pollen.

Pollen	Expected (HF)	Observed (SPT)	Chi-square
Picea	14.90	8.00	3.21
Pinus	13.40	13.10	0.010
Betula	9.50	5.60	1.57
A. crispa	6.00	6.10	0.0045
Salix	3.00	1.60	0.64
Other herbs	5.98	6.10	0.0024
Cyperaceae	42.80	53.30	2.60
Aquatics and spores	3.00	5.10	1.45
Sum	98.50	98.90	9.48

The chi-square statistic was 9.49, with 7 degrees of freedom. The value of 9.49 was less than the critical value of 0.20. Therefore, H_o was again accepted.

The two tests indicated that the two methods of using sodium polytungstate as a heavy liquid separation method and the standard (HF) method, produced pollen assemblages that were not statistically different. Since the heavy liquid produced

material far easier and more efficient to count, due to the increased pollen concentrations per slide, the new method using sodium polytungstate was used in this study. 15 levels (0-0.5, 21-22, 108-109, 168-169, 183-184, 188-189, 248-249, 258-259, 318-319, 338-339, 358-359, 398-399, 423-424, 448-449, 468-469,) that had already been counted while the tests were undertaken were retained for this analysis. This new method of processing Arctic sediments enabled more slides to be counted with a subsequent higher resolution of the resulting pollen diagram. Here is the final protocol for processing Arctic sediment using heavy liquid.

Processing Arctic sediments including heavy-liquid (Sodium Polytungstate (SPT)) concentration of pollen grains

1. Subsample sediment from core and place in vials (or if possible, directly into 50 mL centrifuge tubes. With Arctic sediments, a maximum of 2 cm^3 can be used at one time, otherwise 1 cm^3 should be sufficient. You may need to modify this based on experience with your core. Lake, depth in sediment and tube number should all be noted in lab notebook. Use the standard notebook template to record the details of your processing.
2. In each centrifuge tube, place 2 tablets of *Lycopodium* spike. Note the batch number and number of grains added in the notebook.
3. Add 10% HCl. Use a small amount at first as HCl reacts with the carbonate filler in the *Lycopodium* spike. If needed, empty and clean out the centrifuge vials into the tubes using the HCl. Stir the sediment and HCl together, trying to rid the sample of large clumps of sediment. (Start the water baths now. Watch these periodically and adjust to keep the water boiling)
4. Take the tubes in pairs and balance them on the small plastic balance. Place them in the centrifuge across from one another for 5 minutes at 4000 rpm. Note the proper slots on the diagram on the wall. Make sure that (a) the caps on the 4 buckets are closed and (b) the plastic lid is properly seated. Do not run the centrifuge without the caps and lid, even if the tubes only contain water. After they have spun down, decant the supernatant.
5. Add 2/3 tube of deionized water, stir, centrifuge and decant (called washing).
6. Add 2/3 tube full of 10% KOH. Stir the sediment and place in a boiling water bath for 6-8 minutes. (Generally 8 minutes)
7. Repeat steps 4 and 5.

8. Perform another 2 washes (step 5 another 2 times) to rid excess particulates floating in the tubes.
9. Repeat steps 3 through 5. Making the solution acidic may aid in removing non-pollen material from suspension forcing it to accumulate with the sediment at the bottom of the tubes. (Takeshi 1998) When decanting the water ensure that the maximum possible amount of water has left the tubes. If not, excess water might decrease the density of the SPT.
10. Prepare the Sodium Polytungstate (SPT) solution. This is done by either adding powder to a previously made solution (if necessary), or, if none is available, dissolving the powder in water to form a solution with a density of approximately 1.95. Use a hygrometer to verify your specific gravity. Note that the density of sporopollenin is 1.4. Add 5ml of the SPT solution to each tube and mix on the vortex for five minutes. You can set up a retort holder to hold the tubes in position over the vortex mixer, see picture. Make sure the tubes are capped.
11. When samples are vortexed, they can be centrifuged at 1800 rpm for 10 minutes (8 at a time). The speed is decreased from that typically used in pollen preparation so that pollen is not forced down to the bottom. To balance the tubes, use extra tubes filled with deionized water or other vials. DO NOT add more SPT to your samples.
12. After centrifuging, decant the pollen - the material that floats into another LABELED centrifuge tube. These are now your samples. Make sure to note the second tube number in the lab notebook. It is sometimes necessary to add a small squirt of water into the tubes to ensure all the pollen was decanted. Take the tubes that have the sediment left in the bottom and rinse them out. These are discarded, although you may wish to occasionally make smear slides of this to ensure you are not losing pollen. Be sure to rinse these tubes again with deionized water.
13. Take your pollen (in their new tubes) and the original tubes that you rinsed and split the 5ml of SPT plus pollen mixture between the two. It is now important to fill the tubes up as high as possible with water and to top them off with a squirt of ethanol to decrease the density of the water/SPT mixture, ensuring the pollen sinks to the bottom. *Note that the squirt of ethanol is done at several steps (any time the tubes are primarily water) to break the surface tension and prevent pollen from floating on the water.*
14. Centrifuge at 4000 rpm for 5 minutes.
15. When decanting, take the supernatant SPT/water mixture that you decanted and place into the plastic container labelled "SPT-dirty". *This material will be reused.* This liquid should be filtered using a Buchner funnel and large coffee filter. It should be filtered twice, using a second coffee filter. The liquid is then filtered a second time with a Buchner funnel under a vacuum using a 7μm mesh. The liquid is then placed into a cleaned beaker and placed into the oven at 105°C to evaporate the water and decrease the density of the liquid. You should evaporate a sufficient quantity of water to ensure the density is greater than 1.9,

but it should not be allowed to dry. This cleaned liquid should be placed in the plastic container labelled "Clean SPT", ready to use.

16. The two tubes containing pollen from the same sample are combined using water (remember the squirt of ethanol), centrifuged and decanted.
17. At this point, it is up to the analyst to decide if HF is needed. If the sample is quite silty, then this is recommended. Recall the HF is extremely dangerous, and all protective equipment must be used. In the centrifuge all three caps (centrifuge, bucket, centrifuge) must be used. See the WHIMIS information in the lab.
18. HF is added to each tube, approximately half full, centrifuged and decanted. You can heat it for 12-15 minutes if there is a lot of silt remaining. You can also leave it overnight, cold. If you leave it overnight make sure it is properly labelled.
19. Step 5 is repeated.
20. Now you need to get rid of the water in preparation for acetolysis. Add a 1/2 tube of glacial acetic acid, stir the sediment, centrifuge and decant. If you need to balance the tubes, use glacial acetic acid.
21. Next step is acetolysis. Mix the acetolysis solution in the appropriate bottle. Note that this bottle should have no water. Add the sulphuric acid (10 mL) to the acetic anhydride (90 mL) slowly. See the warnings on the standard pollen protocol page.
22. Add the solution to the tubes; 1/2 full should be sufficient. Carefully place the tubes in the water bath for three minutes. When the time is up, carefully remove them, equalize the amount in the tubes with glacial acetic acid (*not water, nor should you add the ethanol*) and centrifuge. Carefully time your second batch so as not to exceed the three minutes in the water bath. At the end of acetolysis, you can turn off the water bath, but see below.
23. Add a half tube of glacial acetic acid, stir the sediment, centrifuge. *Do not add water at this step.*
24. Add a 1/2 tube of distilled water, stir the sediment, centrifuge.
25. Now you need to do a 95% ethanol rinse. Add 1/2 tube of ethanol, stir the sediment, centrifuge, decant. You can add a drop of saffranin stain to the tube if you wish to stain the pollen grains.
26. Repeat step 25. Don't put in any stain the second rinse, however.
27. Now put in a 1/2 tube of tert-butanol, stir the sediment, centrifuge and decant. See below for comments on butanol. The TBA must be warmed (but not hot) to prevent it from freezing at room temperature. This is especially important in step 29. To heat the butanol, fill a beaker with hot tap water and place the bottle in the hot solution. Change the water periodically if needed. *Do not heat the butanol, nor place it in the water bath on the hot plate.*
28. Step 27 is not usually repeated here (as per normal protocol) to decrease the chances of decanting pollen.
29. You now need to transfer the sediment to the vials where they will be stored permanently. If you rinsed the original vials, and they are dry, you can use them. Make sure they are carefully labelled (and completely dry), and watch during

this procedure, as the butanol can dissolve some inks. You can cover the label information with scotch tape, for example. Add the sediment/butanol mixture and with the butanol wash bottle rinse the tube to get the sediment into the vial. You may need to repeat this step a couple of times, although with practice it can be done in one step. Place the vial in the centrifuge and spin. Decant and repeat if necessary to get all the sediment into the vial.

30. When the sediment is all in the vial and you have decanted the butanol, add a couple of drops of Silicone oil and stir with a toothpick. You can leave the applicator stick in the vial. Place the vials in the Clean Hood (the green one in the core prep room). The clean-hood room is sometimes quite cold and the TBA may freeze before evaporating, in which case you can let it sublimate or place in an alternate, clean location) and allow any remaining TBA to evaporate. When you can no longer smell the butanol (a couple of days if you decanted efficiently), the samples are ready to be used. You can cap them and store them (ensuring they are properly labelled with the lake name, the depth, and if you want, date and your name) until you are ready to identify the grains on the slide.
31. To make a slide, take a drop of the sample and place on the center of the slide, usually, you need to mix some more Silicone oil on the slide to get a good density of material on the slide; this comes with practice. Make a cross on the slide, and put on a cover slip. It is easier to show this than explain it. Use two drops of fingernail polish on two opposite corners to keep the coverslip in place.

Comments:

- All waste must be placed in the proper pail. Be very careful not to mix wastes improperly.
- You can stop the procedure (overnight) at any stage where the sediment is in water (or ethanol).
- With any acid step, and especially HF, you should be careful not to breathe the vapours, nor let any acid tough your skin. Use goggles, a plastic face mask, lab coats, and extreme caution.
- Acetolysis step: when placing the tubes in the boiling water bath, be careful not to drip any water into the tubes. You should always be careful about this to avoid contamination, but especially here to avoid the reaction.
- Ethanol may be used to break the surface tension at any washing step.
- Thanks to A López-Higuera for help with the SPT method.

Data Analysis

A principle components analysis (PCA) was performed on the modern and fossil pollen to aid in the interpretation of the pollen assemblages. Modern samples retained included those that were classified as "Arctic" according to Federova et al (1994) from the modern pollen database (Whitmore et al 2005) and only local and regional pollen

were retained in the pollen sum. "Forest-tundra" sites and long-distance pollen were excluded from this analysis as the initial result (with "Forest-tundra" sites and long-distance pollen included) was difficult to interpret. To understand the diagram, the number of sites and taxa were reduced. Pollen taxa retained can be found in Appendix 1A.

A correlation matrix was used in computing the components. The pollen diagram was dominated by a few species and the local pollen counts were quite low. Therefore, in using a correlation matrix, dominate and rare species were more equally weighed. A first analysis found a site on the southern tip of Greenland to be an outlier that dominated the analysis. When the PCA was performed again without this modern site, a more reasonable result was obtained.

On the biplot, modern sites found with similar scores to the fossil pollen were extracted. The coordinates of these modern pollen were mapped in ArcMap to show the location of the modern sites that can be considered as rough "analogs" for the fossil assemblages.

The Modern Analog Technique (MAT) (Sawada 2006, Overpeck et al 1985) was applied to the fossil pollen assemblages of Lake JR01 to reconstruct July temperatures of the past 7200 years. Modern pollen assemblages classified as "Arctic" and "Forest-Tundra" (Federova et al 1994) in the Modern Pollen Database (Whitmore et al 2005) were retained as calibration samples. Since the vegetation classes in the database are quite generalized, "Forest-tundra" pollen samples were retained to ensure sufficient samples from the shrub tundra were available to find potential analogs. Most pollen taxa included in the modern pollen database (Whitmore et al 2005) were

included in the pollen sum except those that were found in desert areas or the extreme south of the United States (Appendix 1B for taxa retained).

The difference between the fossil and modern pollen assemblages was measured using a squared chord distance (SCD). The modern pollen site with the lowest SCD would indicate that it was the most similar to the fossil pollen (the best analog). Therefore the environmental data of the modern pollen at that particular site, may be applied to the fossil pollen.

Analog analysis was performed using the program MATTOOLS (Sawada 2006) with a Monte Carlo simulation. A Monte Carlo simulation performs comparisons between randomly chosen modern pollen assemblages using a pair-wise comparison. This is done to determine threshold values that are unlikely to occur by chance alone, using a significance level of 0.05 (Sawada 2006). The threshold value indicates analogs below this value. The top five analogs were retained (Sawada 2006) and July temperatures were based on the average of these values. A five point running mean was applied to the reconstructed temperatures to illustrate longer-term trends.

CHAPTER 4 – POST-GLACIAL CLIMATIC CHANGE ON BOOTHIA PENINSULA, NUNAVUT, CANADA

Abstract

A pollen diagram from a lake in the middle-Arctic region of the Boothia Peninsula, Nunavut, Canada, documents the history of the regional vegetation and climate for the past 7200 years. A diatom sequence had been previously prepared from this core. Major tundra pollen taxa in the core include Cyperaceae and *Salix*, with Cyperaceae comprising over 50% of the pollen in the early and late Holocene. Tree pollen, transported from far to the south, comprised a large percentage of the pollen sum, with *Pinus* accounting for 30% of the pollen in some levels of the core. Pollen percentages and concentrations were highest in the middle-Holocene, corresponding to warm conditions. Decreasing pollen concentrations indicated cooling temperatures around 4200, 3800-3400, and 2500 cal yr BP. Pollen percentages of *Salix*, Cyperaceae, and *Artemisia* increased in the past 35 years in response to global warming. Reconstructions of July temperature using the modern analog technique showed the middle-Holocene (5800-2800 cal yr BP) was approximately 1°C higher than during the past 1000 years.

Introduction

The earth's climate is changing and the Canadian Arctic, in particular, is already feeling the impacts of global warming (e.g. Overpeck et al 1997). However, predictions of future climate change impacts are difficult because of the complex response of ecosystems to climate variations. One source of information about possible future impacts is the study of the past. By analyzing how Arctic ecosystems were impacted by past climate changes, we can better infer possible future impacts.

A major proxy indicator of past climates is the pollen produced by plants, some of which are deposited in lake sediments. Pollen assemblages are related to the vegetation, which, in turn, is related to the climate (Bennett and Willis 2001). Therefore, pollen diagrams prepared from lake sediment cores document the history of the regional vegetation through time. Using various numerical analyses, the modern pollen assemblages can be related to the modern climate and these relations, in turn, can be used to estimate past climates (Gajewski 2002). However, there have been few pollen diagrams prepared from the Canadian Arctic (Gajewski and Atkinson 2003).

At present, only a few pollen diagrams have been prepared from the Canadian Arctic and Greenland. Several pollen records have been prepared from the coastal regions of Greenland (Fredskild 1997; Fredskild 1973; Wagner et al 2000, among many others). Pollen records from Arctic Canada include studies from Ellesmere Island (Hyvarinen 1985), Prince of Wales Island (Gajewski and Frappier 1995), Somerset Island (Gajewski 1995) and Banks Island (Gajewski et al 2000) as well as several pollen diagrams from Baffin Island (Andrews 1979; Short et al 1989; Wolfe et al 2000). Modern samples for use in calibration are available from Banks (Ritchie et al 1987),

Somerset (Gajewski 1995), Ellesmere (Gajewski et al 1995) and Baffin Island (Kerwin 2004), as well as a set of samples from central and eastern Arctic islands (Gajewski 2002).

Although these studies have provided descriptive estimates of the climates of the Arctic during the Holocene, there still remain questions about the postglacial climates of the region (Gajewski and Atkinson 2003). Several deficiencies have been identified, including a low density of sites, a low temporal resolution of the existing pollen diagrams and problems with radiocarbon dating of the cores (Gajewski et al 1995; Gajewski and Atkinson 2003; Bigelow et al 2003; Kauffman et al 2004).

This study reports a new pollen diagram from a lake on the Boothia Peninsula. The diatoms from this core had been previously analyzed (LeBlanc 2002; LeBlanc et al 2004). The pollen diagram was prepared at higher temporal resolution than previously published studies and sediment analysis (including sediment loss-on-ignition-LOI) was performed at high resolution. Past climates were estimated using the Modern Analog Technique (MAT). The analysis of the pollen assemblages from this core, along with the quantitative estimation of the past climate, will be a step toward the goal of providing a network of sites in the Arctic islands that document the Holocene climatic history.

Site Description

The study site, Lake JR01 (Figure 2; 69°54'N, 95°4.2'W, 120 m.a.s.l.) is located in the southwestern part of the Boothia Peninsula. The bedrock in the region of the consists of Precambrian Shield. Boothia Peninsula is a plateau with low, rolling hills characterized by thick glacial deposits and little relief (Dyke 1984). The region is in the

middle-Arctic vegetation zone near the transition to the low-Arctic, with continuous herbaceous cover dominated by *Dryas, Salix* and S*axifraga* tundra (Bliss 1988). Climate data from nearby Pelly Bay, Taloyoak and Shepherd Bay indicate cold, dry winters and short, cool damp summers (Dyke 1984, from Atmospheric Service, 1975). The site is closest to the community of Taloyoak (location: 69°32'N, 93°31'W) which has a mean annual temperature and precipitation of -15.4° and 153.4 mm respectively (Dyke 1984, from Atmospheric Service 1975). Lake JR01 is approximately 700 by 350 metres in size with two small stream inputs that enter the lake via sedge meadows (LeBlanc 2004). It is a typical Arctic oligotrophic lake with pH of 8.10 and water conductivity of 220 $\mu S \cdot cm^{-1}$ (LeBlanc 2004).

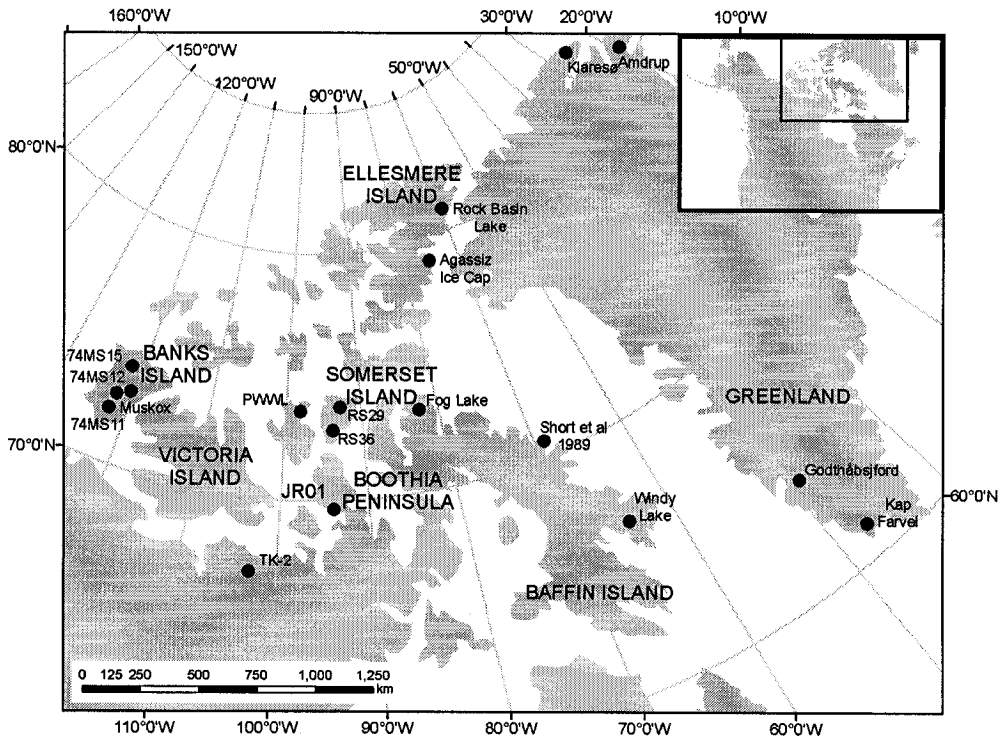

Figure 2: Location of pollen studies in the Canadian Arctic and Greenland.

Methods

Lake sediment cores were collected from Lake JR01 (unofficial name) on the Boothia Peninsula, Nunavut with a 5 cm diameter Livingstone corer through 5.4 metres of water from an ice surface. The base of the lake sediment was not reached due to an insufficient number of drive rods, nevertheless, the core did reach sediments dating to 7200 cal yr BP. The uppermost part of the sediment (0.8 metres) was sampled in a plastic tube with piston, to ensure that the sediment-water interface was collected. The upper 20 cm of sediment were subsampled into plastic bags at 0.5 cm intervals; the remainder of the core was stored at 4°C in plastic wrap and aluminium foil (LeBlanc 2004).

Every cm down the core, 0.5 cm^3 samples were extracted for loss-on-ignition (LOI) analysis. The samples were ignited at 550°C for four hours and at 950°C for a further two hours to obtain estimates of the organic and carbonate content.

Two cm^3 of sediment were extracted at intervals down the core for pollen analysis. Sediment was processed using standard methods of Faegri and Iverson (1989) with the addition of a heavy liquid separation step for most samples. Two tablets of *Lycopodium* were added to each sample to enable the calculation of pollen concentrations (Bennett and Willis 2001). All samples were treated with 10% HCl, 10% KOH and acetolysis solution (Faegri and Iverson 1975). Some samples were treated with concentrated HF and sieved through a 7 μm fine mesh after soaking in warm sodium-pyrophosphate (Cwyner et al 1979). In the remaining samples, pollen grains were separated from the sediment matrix using sodium polytungstate with a specific gravity of 1.95 instead of adding HF. Several wash steps and another 10% HCl

treatment were also performed when using the sodium polytungstate method. A comparison between replicates of the same sample processed using the two methods showed no statistical difference in the pollen counts (Zabenskie 2006), so all samples processed using both methods are used in this study. Silicon oil was added to each sample for final storage.

Small aliquots of the processed sediment were placed on a slide and the pollen grains were counted under a microscope at 400x. The pollen grains were compared to the pollen reference material, as well as texts such as Faegri and Iverson (1975), McAndrews et al (1973) and Kapp (2000) under 1000x oil immersion for critical identification. A pollen sum of at least 300 grains was generally achieved for each level. Typically, several slides had to be counted at each level to obtain this pollen sum due to the low concentration of pollen grains in the sediments. The pollen sum for each level was calculated by summing the total pollen (trees, shrubs, herbs and spores) for that level.

Chronology

The chronology for this core was determined using ^{210}Pb for the uppermost sediments and ten radiocarbon dates for the remainder of the sequence. Nine bulk sediment samples in one-cm increments were sent to MyCore Scientific Inc., Deep River, Ontario for ^{210}Pb analysis. Plant material, larval chironomid head capsules and other chitinous material were picked from five sections of the core (from a maximum of 3 cm for each section) and sent to Beta Analytic Inc., Miami, Florida for ^{14}C analysis. The oldest date was obtained from a second core that had been correlated to the first

sequence using magnetic susceptibility. Several dates, previously obtained (LeBlanc et al 2001), were also used. Calib501 (Reimer et al 2004a) was used to convert the radiocarbon ages to calendar year ages. The mean of the "sigma two" values was used as the calibrated radiocarbon ages (Reimer et al 2004a). Sample ages were estimated by linear interpolation between the calibrated ^{14}C ages and the ^{210}Pb ages for the uppermost sediment.

A principle components analysis (PCA) was performed on the combined modern and fossil pollen to aid in the interpretation of the fossil assemblages. Modern pollen were obtained from Whitmore et al (2004). Only sites designated as "Arctic" under the Federova et al (1994) scheme were retained. A pollen sum only of local and regional pollen (See Appendix 1B for taxa) was used in the PCA and a correlation matrix was utilized to equally weigh the dominate and rare pollen taxa.

July temperatures were estimated from the fossil pollen assemblages using the modern analog technique (MAT) (Sawada 2006). Modern pollen and climate data were obtained from Whitmore et al (2004). Sites designated as "Arctic" and "Forest-tundra" were retained as possible analogs. A pollen sum of long-distance and local and regional pollen was used.

The difference between the fossil and modern pollen assemblages was measured using a squared chord distance (SCD). The modern pollen site with the lowest SCD would indicate that it was the most similar to the fossil pollen (the best analog). Therefore the environmental data of the modern pollen at that particular site, may be applied to the fossil pollen.

Analog analysis was performed using the program MATTOOLS (Sawada 2006). The top five analogs were retained (Sawada 2006) and July temperatures were based on the average of these values. A five point running mean was applied to the reconstructed temperatures to illustrate longer-term trends. A second reconstruction was performed, only using sites designated as "Arctic" by Federova et al (1994) and a pollen sum of local and regional pollen (See Appendix 1A for taxa).

Results

Chronology and Sediment Stratigraphy

A 4.84 metre sediment core was collected from Lake JRO1 (unofficial name). The core is mostly homogeneous in colour, except for light banding in the lowest two metres (LeBlanc 2002). Unsupported ^{210}Pb was detected within the uppermost nine cm of the core with the amount of ^{210}Pb decreasing to this level. A constant rate of supply model was used to derive the ages. The radiocarbon and ^{210}Pb series provided a reliable chronology with no age reversals (Table 5; Figure 3). Sedimentation rates varied between 0.02-3.6 cm/year for the past 5600 cal yr BP, with a general trend toward a decreasing sedimentation rate in the more recent past. In older sediments, the sedimentation rate was greater, but variable.

Table 5: Radiocarbon dates used to establish the chronology used by LeBlanc (2002) are indicated by a * in column 1. Calibrated ages were based on mean of "Sigma two" values.

Depth (cm)	^{14}C year BP	Lab. No.	Calibrated Calendar year BP
30-35*	1290 +/- 40	Beta-156532	1195
59-61	2120 +/- 40	Beta-204646	2146
95-100*	2410 +/- 40	Beta-156533	2522
153-154	3030 +/- 40	Beta-204647	3219
220-225*	4290 +/- 40	Beta-156534	4850
295-300*	4890 +/- 40	Beta-156535	5651
349-350	4990 +/- 40	Beta- 210910	5746
395-396	5000 +/- 40	Beta-204648	5758
453-456	6160 +/-40	Beta-204649	7057
544-549*	6320 +/- 40	Beta-156536	7286

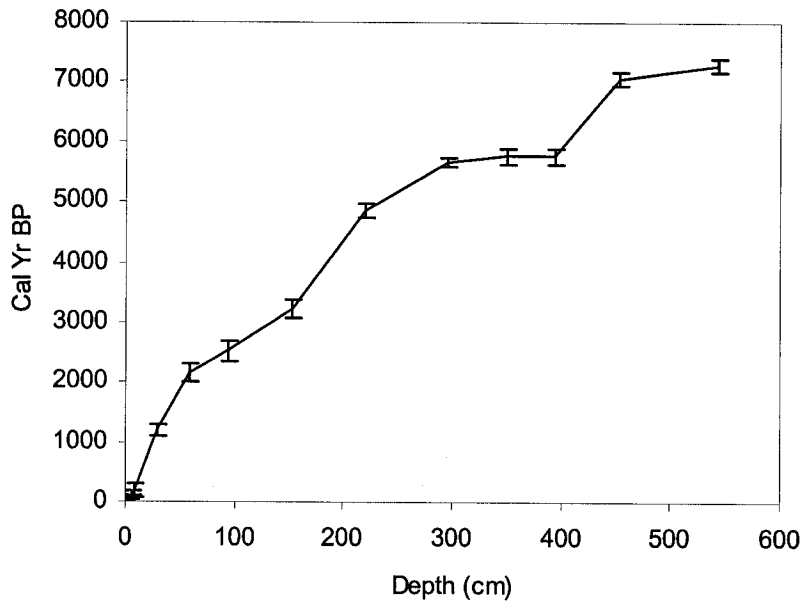

Figure 3: Age-depth curve for lake JR01.

The organic and carbonate content generally have an inverse relationship along the length of core JRO1 (Figure 4). Loss on Ignition (LOI) is inversely related to magnetic susceptibility as well. LOI remained constant from the base of the core to ~6300 cal yr BP at approximately 27%. It then increased to above 30 and remained high until ~4900 cal yr BP. LOI then slowly decreased, with a sharp decrease at 4400 cal yr BP to a value of 20%, returning to 27% by 4000 cal yr BP. Between ~2600 and ~2460 cal yr BP organic content values decreased to 20%, increasing again after ~2460 cal yr BP. In AD 1961, the organic content reached a low of 12%; then increased steadily reaching values greater than 33% in AD 1977. Carbonate content estimated by ignition at 950°C showed an inverse trend to that of LOI, although changes were not as abrupt.

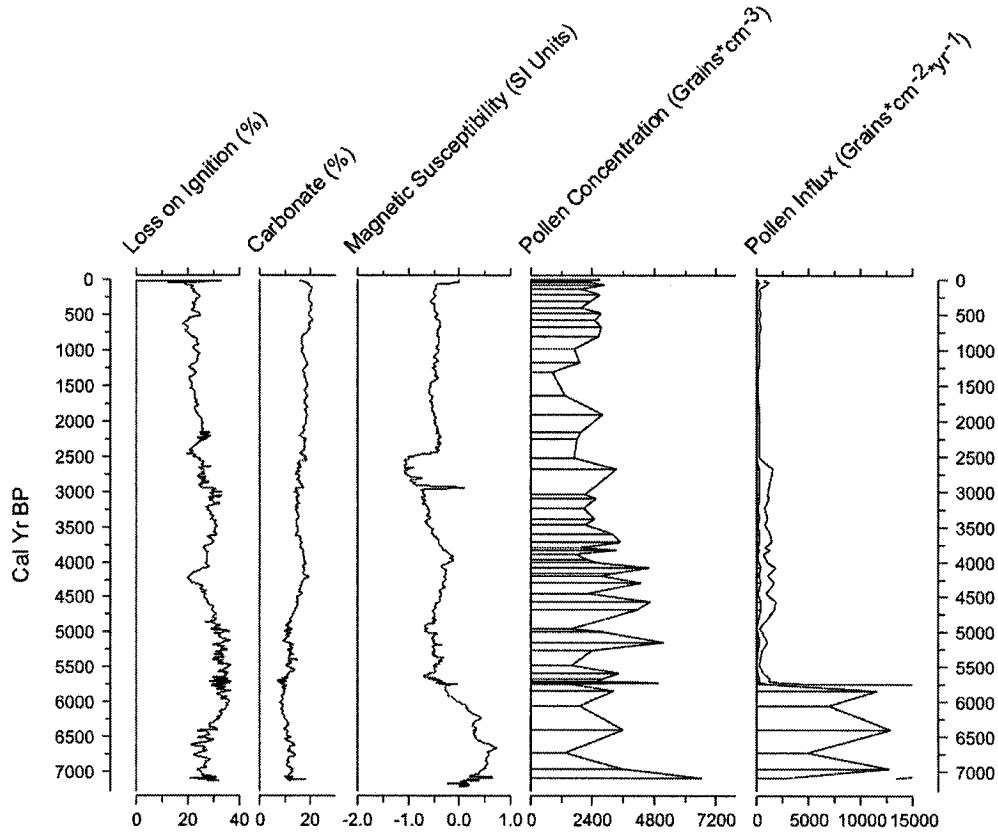

Figure 4: Sediment parameters, pollen concentrations and pollen influx of Lake JR01. A second curve on the influx graph corresponds to a 5x exaggeration.

The maximum values of magnetic susceptibility occurred in the early portion of the record (LeBlanc 2002). Values decreased until 5700 cal yr BP, then remained relatively low but variable until 4700 cal yr BP. Magnetic susceptibility then increased slowly until ~4000 cal yr BP, during a period of decreasing organic matter. At ~4000 cal yr BP magnetic susceptibility values started to decrease, reaching lowest values at ~2600 cal yr BP, in parallel with LOI. A large peak at 2948 cal yr BP is attributed to a pebble in the core (LeBlanc 2002). Magnetic susceptibility increased sharply between 2600 to 2430 cal yr BP and remained constant for the remainder of the core.

Total pollen concentrations were highest in the early Holocene reaching up to 6400 grains/cm^3. Concentrations decreased after ~4000 cal yr BP, reaching lowest values between ~2600 and ~800 cal yr BP. Pollen concentration increased between ~1500 and ~750 cal yr BP and remain steady at approximately 2400 grains/cm^3 for the past 1000 years. Pollen influx values were highest prior to 5750 cal yr BP. Influx greatly decreased at a time coinciding with a change in the sedimentation rate (Figure 4). Influx again decreased approximately 2500 cal yr BP and increased slightly during the past 750 years.

Pollen Stratigraphy

Cyperaceae is the most abundant taxon with percentages reaching greater than 50% in the early part of the core and in the uppermost few pollen spectra. There was a long term decreasing trend in Cyperaceae pollen percentages during the past 7000 years. Values were high prior to 5700 cal yr BP then decreased between 5700 and 2700 cal yr BP. Between ~2700 and ~1500 cal yr BP, Cyperaceae pollen percentages

decreased; this was followed by an increase ~1000 cal yr BP and a decrease within the uppermost sediment. During the past 40 years, Cyperaceae pollen percentages again increased, reaching values close to 60%.

Salix pollen percentages were generally highest in the early Holocene with values at 4% decreasing to 0.6% by 5600 cal yr BP. Salix percentages remained between 0.5-4% through most of the core. Again, *Salix* pollen percentages increased in 1965 to over 8%, the highest values attained in the record.

Included in the category "local and regional pollen" are taxa from plants today growing on the tundra of Boothia Peninsula. Many of the percentages of local and regional pollen taxa were found with values below 1% and slightly higher for Poaceae and *Artemisia*. Higher values of *Oxyria* and Chenopodiaceae pollen percentages were found in the early Holocene. Several other taxa, including Poaceae, Caryophyllaceae, Brassicaceae and *Artemisia* had higher pollen percentages in the late Holocene. For example, pollen percentages of Brassicaceae decreased to 0 between ~4200 and ~2700 cal yr BP, with percentages in the early part of the core close to those found in the late Holocene. Pollen percentages of several taxa, including *Plantago major, Polygonum viviparum,* Ranunculaceae, *Papaver,* Rosaceae, *Potentilla and Rubus chamaemorus* were generally absent from the base of the core until ~5600 cal yr BP. Between ~5700 to ~5600 cal yr BP, few pollen grains of Chenopodiaceae, Asteraceae, Fabaceae, *Oxyria, P. major, P. viviparum,* Ranunculaceae, *Papaver,* Rosaceae, and Saxifragaceae were counted (Figure 5). Few pollen grains of taxa such as *P. major, P. viviparum,* Ranunculaceae and *Papaver* were found from ~2600 to ~750 cal yr BP.

Long-distance pollen constitutes pollen of plants that are not currently growing in the region. These are mostly tree pollen, but some shrub pollen found in the forest-tundra (notably *Betula* and *Alnus*) are included here. Long-distance pollen accounts for a majority of the pollen found in the core, with *Pinus* alone accounting for 30% of the pollen in some levels. *Pinus* percentages were low prior to 5500 cal yr BP, with values of 10%. Values increased to 20% by ~4500 cal yr BP and slowly increased during the middle and late Holocene. Superimposed on this long-term trend were periods of lower values, most notably at 4200, 3200-2500 and 1200-500 cal yr BP. *Picea* percentages were more constant in the core at approximately 10%. Minimum values were found between ~2500 and ~1250 cal yr BP.

Betula and *Alnus* pollen percentages were highest in the early part of the core at 13% each and the curves of the two taxa were generally parallel during the entire sequence. At ~5700 cal yr BP, percentages gradually decreased to a few percent by ~5500 cal yr BP and maintaining this value through the rest of the core. Smaller fluctuations were apparent in both curves, for example, a short period of lower values between ~3600 and ~3150 cal yr BP.

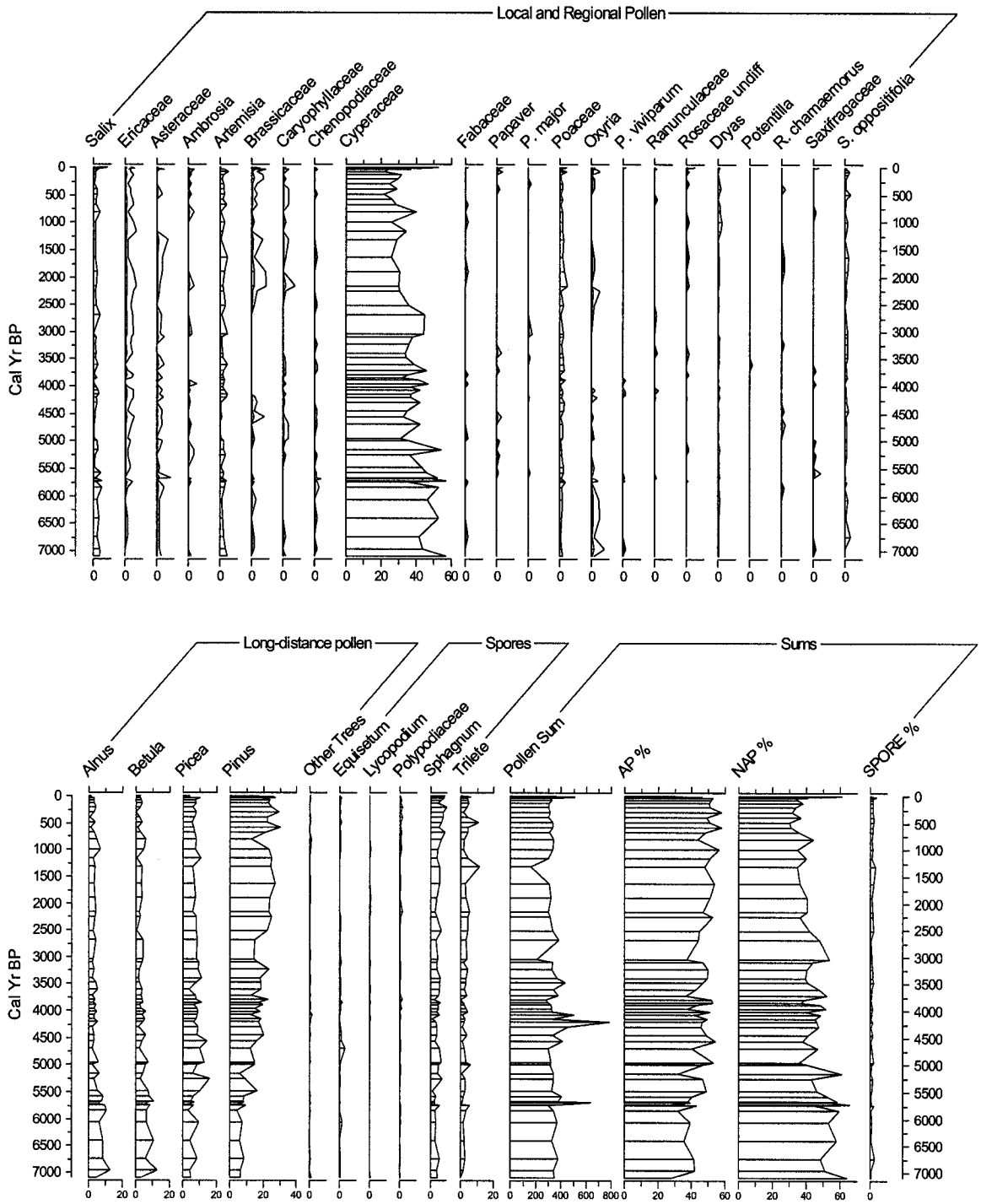

Figure 5: Pollen percentage diagram of Lake JR01. Pollen sum is total pollen and spores. A second curve on selected graphs corresponds to a 5x exaggeration.

Numerical Analyses

Component 1 explained 9.1% of the variance and component two explained 6.3% (Figure 6). Taxa highly loaded on the first principle component included *Betula*, Ericaceae, and Lycopodiaceae (positive) and *Dryas, Papaver*, Caryophyllaceae, Brassicaceae, *Rumex/Oxyria*, Saxifragaceae and *Saxifraga oppositifolia* (negative). Taxa highly loaded on the second axis included *Lycopodiaceae*, *Polypodium*, *Thalictrum* and Poaceae (positive) and *Artemisia*, Cyperaceae, and *P. viviparum* (negative) (Figure 7).

All fossil pollen levels were negatively loaded on component 2. Several modern samples had comparable scores to the fossil taxa suggesting similar pollen assemblages.

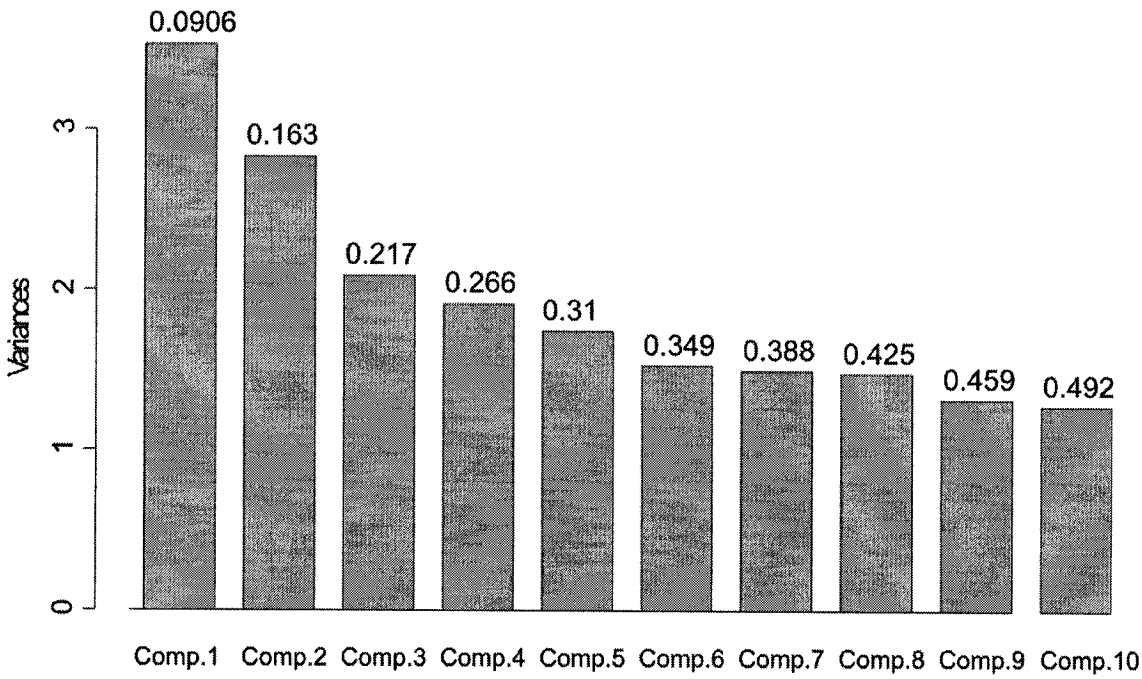

Figure 6: Scree plot of the eigenvalues of a PCA on the combined modern and fossil pollen assemblages. Numbers over the bars are the explained variance of the component. See text for details.

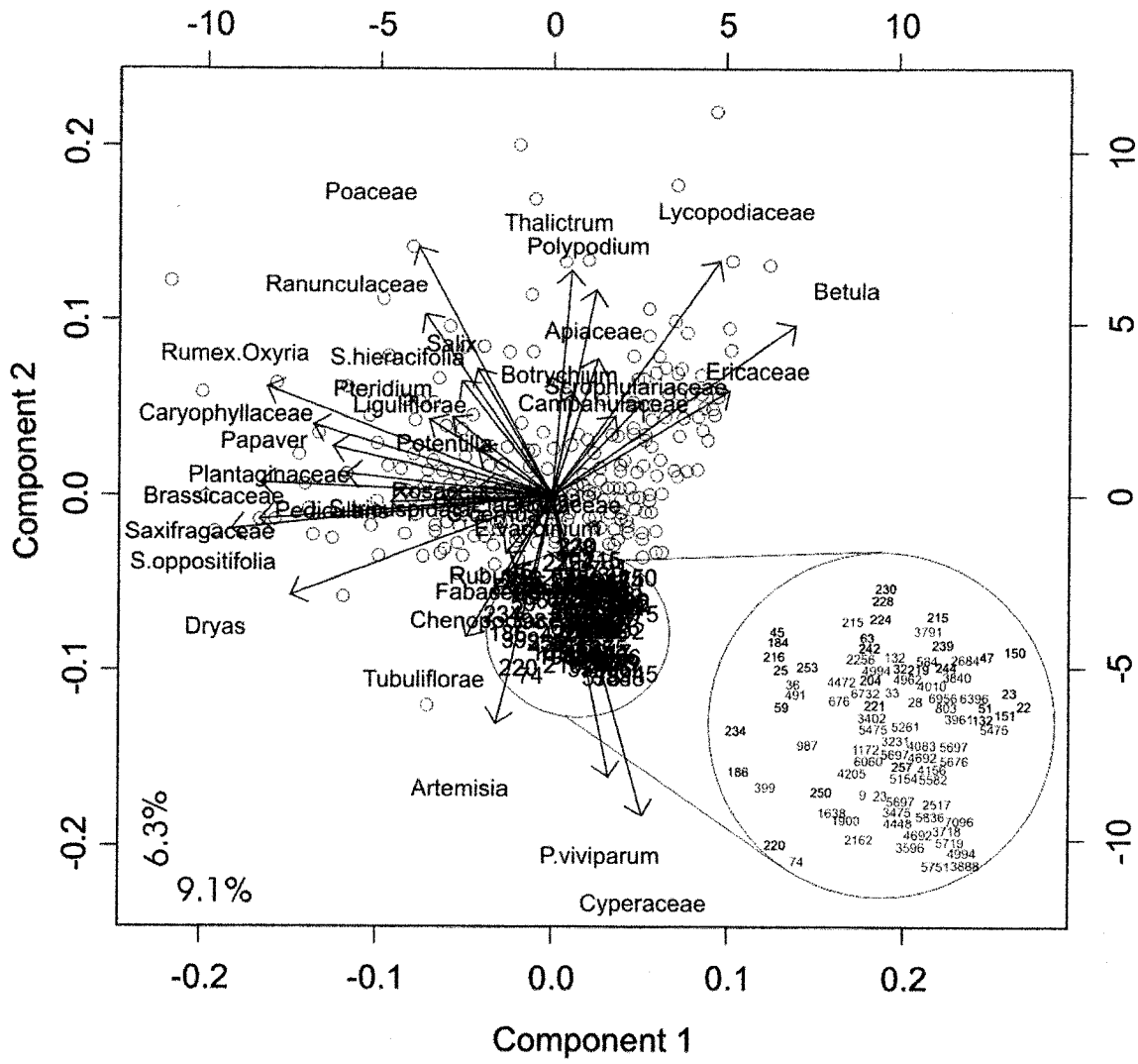

Figure 7: Principle components analysis of fossil pollen from Lake JR01 (red) and modern (black) pollen samples from Whitmore et al (2005). "Arctic" sites from Federova et al (1994) were selected, and the pollen sum consisted of only local and regional pollen. Numbers are sample code (see Appendix 5). Circle encompasses fossil samples and modern samples that were mapped in Figure 8.

Modern samples that had similar scores as the fossil samples (Figure 7), were mapped to illustrate the location of general "analogs" to the fossil samples (Figure 8). In general, modern samples from the southern and eastern Arctic most closely resemble those of the fossil pollen spectra.

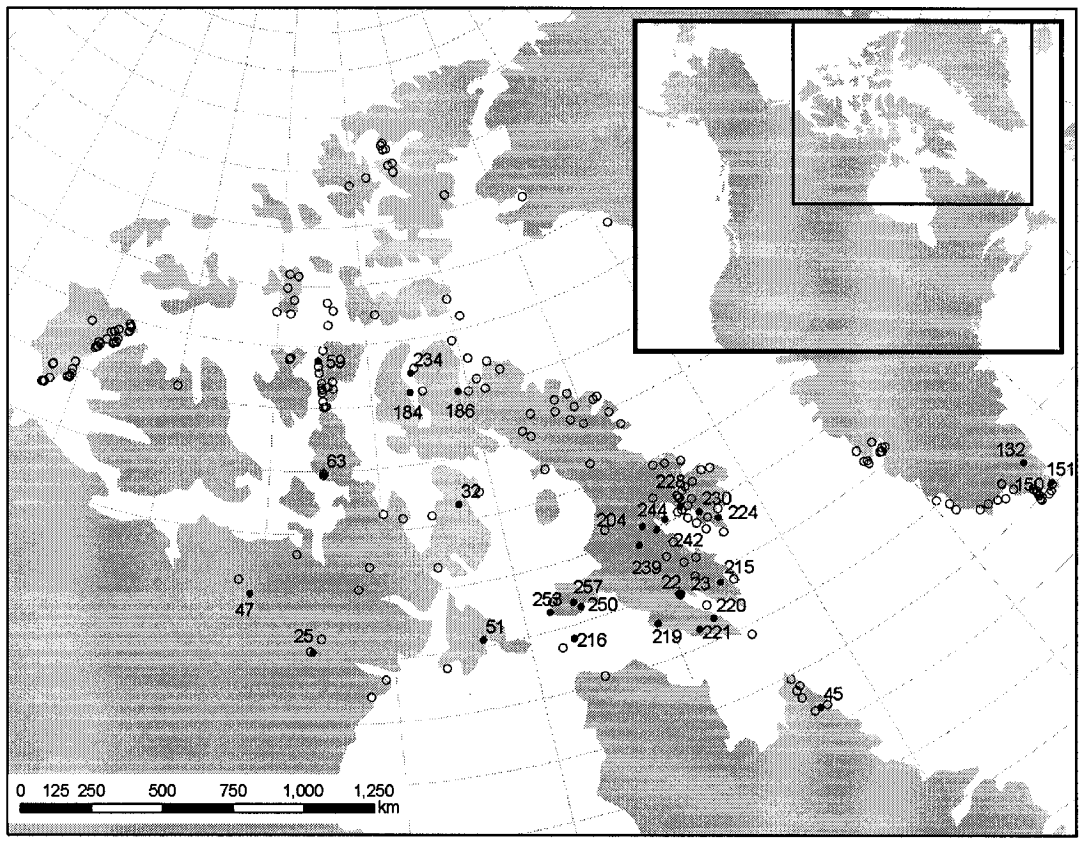

Figure 8: Map of modern pollen sites that ordinate in the same general position with the fossil pollen (closed circle) and those modern sites not relating to the fossil pollen (open circle) as determined by the PCA.

Reconstructed mean July temperatures remained around 6.6°C before ~5700 cal yr BP (Figure 9). July temperatures then increased to 7.8°C between ~5700-3800 cal yr BP; temperatures have decreased slightly during the past 3800 years. Dissimilarity values were generally constant hovering at around 0.16 although they were slightly lower in older samples (Figure 10).

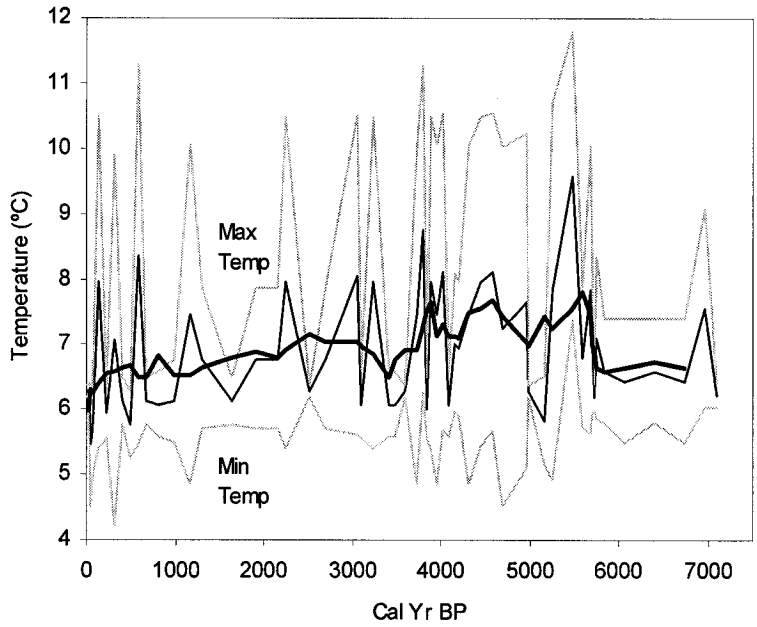

Figure 9: Temperature reconstruction of Lake JR01 using 5 analogs. Middle line represents the average of the maximum and minimum temperatures. Solid thick line represents the 5 point running mean.

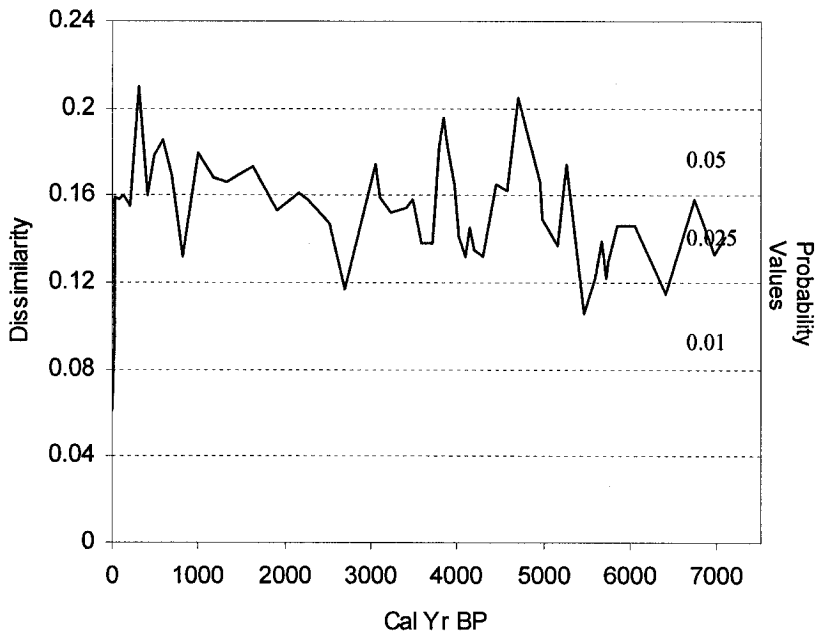

Figure 10: Dissimilarity values of the temperature reconstruction on Lake JR01.

A second reconstruction using only "Arctic" sites as classified by Federova et al (1994) and based on a pollen sum of local and regional pollen was performed (Appendix 1A). Reconstructed temperatures using only local and regional pollen were colder than temperatures reconstructed using local, regional and long-distance pollen. This second July temperature reconstruction had a high of 7.3°C and low of 6.3°C. General trends are similar to those found when all pollen were included in the sum although the variability is less. Temperatures increased in the last 40 years when only local and regional taxa are included in the pollen sum; when long-distance pollen were included in the reconstruction, temperatures continued to decrease in the upper sediments. Dissimilarity values typically remained between 0.08 and 0.2.

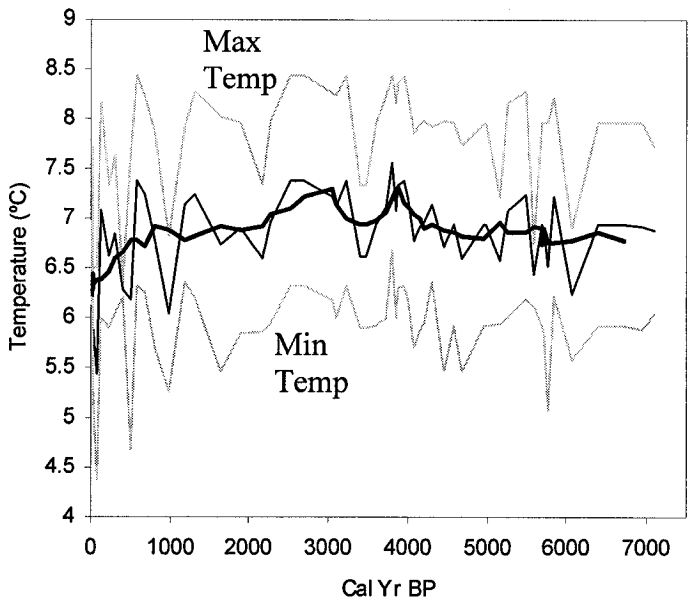

Figure 11: Temperature reconstruction of Lake JR01 using only "Arctic" modern pollen sites and using a sum of local and regional pollen. Middle line represents the average of the maximum and minimum temperatures. Solid thick line represents the 5 point running mean.

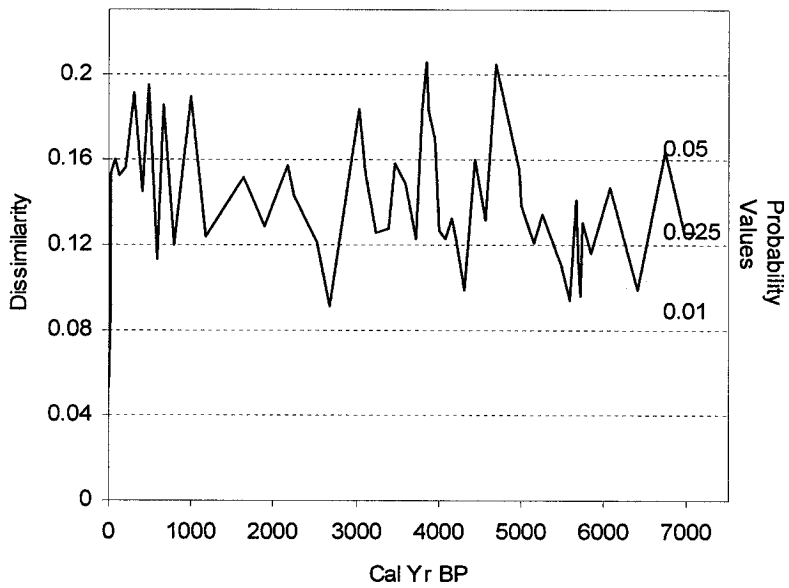

Figure 12: Dissimilarity values of the temperature reconstruction using only "Arctic" sites and a pollen sum of local and regional pollen.

The modern pollen sites chosen as first analogs for each fossil pollen level (as determined by the MAT) were mapped (Figures 13 and 14). When long-distance and local and regional pollen are included in the pollen sum (Figure 13), only a few modern sites were chosen as analogs and all were from the low or middle-Arctic tundra. This would indicate that JR01 did not experience high-Arctic conditions.

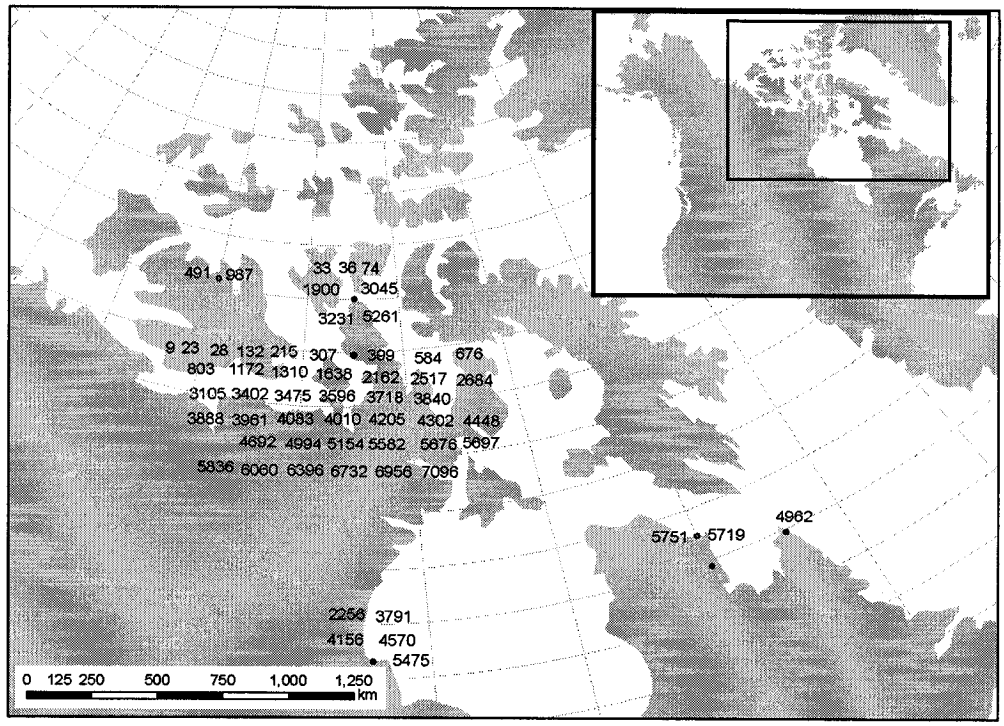

Figure 13: Map of first analogs for fossil pollen using "Arctic" and "Forest-tundra" sites with a pollen sum of local and regional and long-distance taxa (Appendix 1B). Numbers on map correspond to fossil level cal yr BP ages.

When only local and regional pollen were included in the pollen sum (Figure 14), modern sites chosen for analogs were located in similar areas to those found above, yet sites were not as far south (Manitoba).

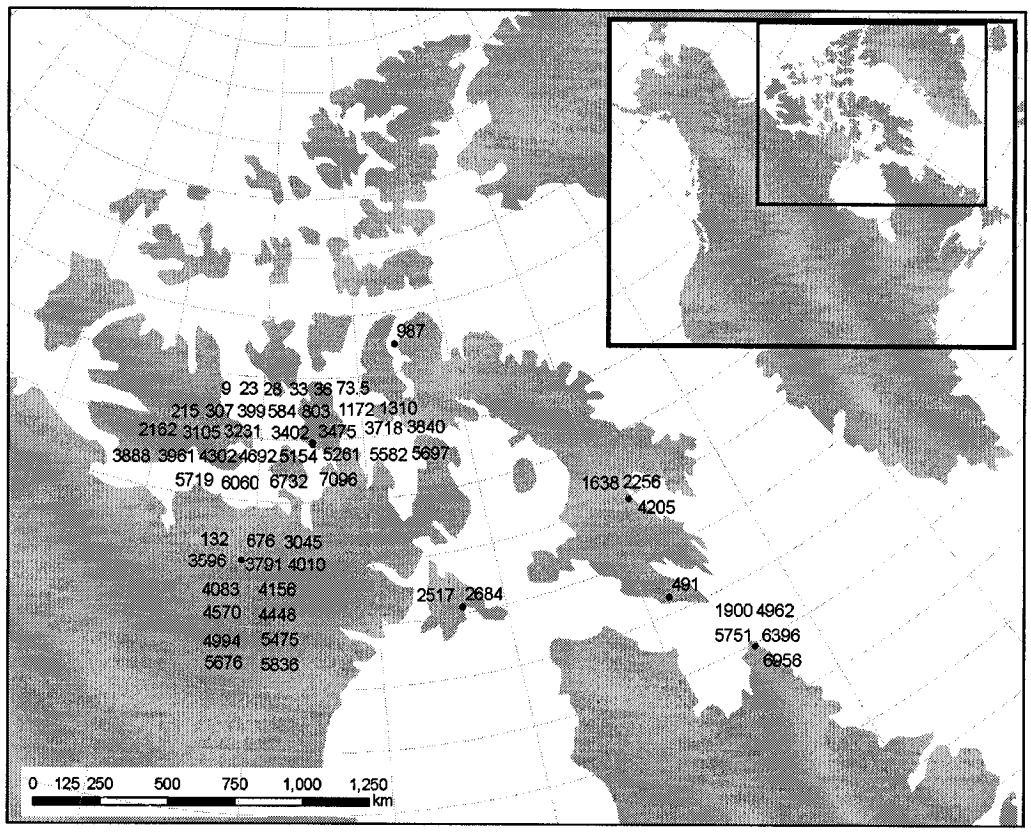

Figure 14: Map of first analogs for fossil pollen using local and regional taxa only from "Arctic" sites (Appendix 1A). Numbers of map correspond to fossil level cal yr BP ages.

Discussion

Maximum estimated July temperatures were reached between ~5800 and ~3800 cal yr BP, at which time they exceeded present-day values. High diatom concentrations and high productivity also occurred during this time and were interpreted as warmer temperatures (LeBlanc et al 2004). During this same time, magnetic susceptibility values were at intermediate levels, suggesting a reliable stable landscape.

A brief period of low temperatures between 5500 and 5000 cal yr BP was interpreted from a decrease in *Salix,* Fabaceae and Cyperaceae pollen percentages. During this time, percentages of pollen taxa transported from the south such as *Alnus*

and *Betula,* also decreased. This was followed by a brief period of high temperatures between 4500 and 3800 cal yr BP, corresponding to increases in Cyperaceae and *Salix* pollen. Cyperaceae and *Salix* pollen taxa are more abundant middle-Arctic pollen spectra (Gajewski 2002), indicating warmer temperatures.

After 4200 cal yr BP, reconstructed temperatures decreased at the same time as a sharp decrease in loss-on-ignition and increase in carbonate content values. Total pollen concentrations increased, due to increased input of *Pinus* pollen. Between 3800-3400 cal yr BP, shrub pollen transported from the low-Arctic, including *Betula* and *Alnus*, decreased and reconstructed temperatures therefore decreased. Pollen percentages of local and regional taxa, including Cyperaceae and *Oxyria* decreased as well. *Oxyria* pollen are more abundant in high-Arctic pollen samples (Gajewski 2002). Temperatures increased again to 7°C at 3100 cal yr BP, as the pollen percentages returned to their values before the cooling.

Between 2500 cal yr BP and the present, temperatures further decreased. During this time, pollen of taxa that are more abundant in high-Arctic samples, including Poaceae, Brassicaceae and *Oxyria* increased, while percentages of Cyperaceae, *Salix,* and *Dryas* decreased. *Pinus* pollen percentages increased during this time, while other long-distance pollen (*Alnus, Picea* and *Betula*) decreased. *Pinus* pollen may be increasing during cooling periods simply because of the constraints of percentage calculations; as input of pollen from other taxa decreased, *Pinus* pollen, produced in large quantities and efficiently transported by wind increased as a consequence. At this same time, loss-on-ignition decreased and magnetic susceptibility sharply increased.

LeBlanc (2002) also interpreted a cooling at this time, based on decreasing diatom diversity.

A short warming, which could be interpreted as the Medieval Warm Period, occurred between 900-750 cal yr BP. The diatom production changed at this time, also interpreted as a warming (LeBlanc 2002). The warming is indicated by small increases in the pollen percentages of *Alnus, Betula, Salix* and Cyperaceae and decreased pollen percentages of *Pinus*. Following this warming, temperatures cooled during the Little Ice Age again as pollen percentages returned to their values before the warming. There were changes in the diatom assemblage at this time (LeBlanc et al 2004) coinciding with the decrease in pollen percentages and cooler temperatures.

During the last 150 years, a diverse and productive diatom flora was interpreted by LeBlanc (2002) as a consequence of recent warming. Pollen concentrations and loss-on-ignition values also increased at this time suggesting warmer conditions as did percentages of *Salix, Artemisia,* and Cyperaceae pollen. However, July temperatures reconstructed using the MAT remained stable during this time. This may be due to (a) the lack of vegetation response to the rapid warming, (b) the few surface samples available for reconstruction or (c) the use of an average of the temperature from the top five analogs in estimating past temperatures. The mean daily temperature at Taloyoak is 7.1°C (Dyke 1984, from Atmospheric Service 1975), which is warmer than the temperature reconstructed for Lake JR01. The difference between Taloyoak and the reconstructed temperature is probably because five analogs are averaged when deriving the reconstructed temperature and the long-distance pollen (indicators of warm air transport from the south) do not significantly increase during this period.

The high frequency variability in the unsmoothed temperature reconstruction may be due to the following reasons. Pollen taxa found in Lake JR01 are derived from plants, many of which have wide ranges, including some that are circumpolar. Surface samples are lacking in the Arctic, therefore, a fossil sample could find comparable percentages in modern samples located a long distance away. Many of the surface samples in the southern part of the range were moss polsters allowing for poorer analogs due to differential pollen capture efficiency of many polsters and lake sediments. Finally, the use of a coarse gridded climate dataset will make the reconstruction appear more variable. A better gridded climate dataset and more surface samples would allow for better analogs.

Magnetic susceptibility values tended to increase during periods interpreted as cooler temperatures probably due to increased amounts of erosion due to reduced plant cover. Higher influx levels prior to 5750 cal yr BP are attributed to an increased sedimentation rate as influx levels were quite stable throughout the Holocene.

Pollen concentrations are generally quite low in Arctic sediments. Compared with other studies in the Canadian Arctic, such as Somerset Island (Gajewski 1995; where concentrations were 4500 grains/cm^3 in the early Holocene), Lake JR01, a middle-Arctic site, had very high pollen concentrations. Concentrations were also lower on Prince of Wales Island (Frappier and Gajewski 2001) where values only reached a maximum of 1500 grains/ cm^3 in the middle-Holocene. Concentrations reached maximum values of 6000 grains/cm^3 in the early part of the core with values decreasing to 2000-4000 grains/cm^3 in recent sediments. In the high-Arctic of Ellesmere Island,

(Baird Inlet; Hyvarinen 1984) maximum pollen concentrations of 2000 grains/cm^3 occurred in the early Holocene.

The general stratigraphy of both the pollen percentages and pollen concentrations correspond with other pollen studies in the Arctic. Because the temporal resolution of most previous studies is coarse, only broad-scale comparisons can be made. Summer temperatures at Lake JR01 were lower in the early Holocene, as was interpreted on Banks Island (Gajewski et al 2000) and TK-2, a site in the low-Arctic of Continental Canada (Seppa et al 2003). Temperatures warmed in the middle-Holocene, as shown by higher pollen percentages of Cyperaceae, *Dryas, Betula,* and *Alnus*, consistent with the interpretation of sites on Prince of Wales Island (Gajewski and Frappier 2001), Somerset Island (Gajewski 1995), Baffin Island (Short et al 1989), Banks Island (Gajewski et al 2000) and the low-Arctic (TK-2; Seppa et al 2003). The middle-Holocene warming generally occurred between ~6500-5500 cal yr BP, as was interpreted for diatom assemblages of Lake JR01 (LeBlanc et al 2004). A late Holocene cooling at JR01, estimated at around 0.75°C, was recorded, occurring after ~4000 cal yr BP on Prince of Wales (Gajewski and Frappier 2001), Somerset Island (Gajewski 1995), Ellesmere Island (Hyvarinen 1984), Baffin Island (Short et al 1989), Banks Island (Gajewski et al 2000) and at TK-2 in the low-Arctic (Seppa et al 2003). A cooling on Baffin Bay (Andrews et al 1979) occurred later than at JR01, perhaps due to its location further east, although chronological problems cannot be excluded.

The vegetation found throughout the Holocene at Lake JR01 could be interpreted as an herbaceous tundra dominated by Cyperaceae and *Salix.* Slight changes

in local pollen percentages and concentrations during the Holocene suggest changes in vegetation density on the landscape, but still remaining middle-Arctic tundra vegetation.

Summary

A 4.84 metre lake sediment core was analyzed at high resolution for pollen and sediment characteristics. An age-depth chronology was determined using ten calibrated radiocarbon dates and nine ^{210}Pb dates. Major pollen taxa in the core include Cyperaceae, *Salix, Picea, Pinus, Alnus,* and *Betula.* Increases of Poaceae, Brassicaceae and *Oxyria* were interpreted as being caused by cooler temperatures, as these pollen taxa are more abundant in modern high-Arctic samples (Gajewski 2002). Warmer temperatures were interpreted by increases in Cyperaceae, *Salix, Betula, Picea* and *Alnus*. Increases in Cyperaceae and *Salix* were interpreted as warming because they are more abundant in middle to low-Arctic pollen assemblages. Higher percentages of the long-distance pollen were interpreted as warming because higher percentages would indicate stronger southerly winds.

As reconstructed using the modern analog technique, temperatures were cooler prior to 5700 cal yr BP, warmed during the middle-Holocene and cooled after 3800 cal yr BP. The temperature reconstruction in this study agrees with the interpreted temperatures in other pollen studies in Arctic Canada and with a diatom analysis of the same core (LeBlanc 2002).

Acknowledgements

This work was supported with grants to Konrad Gajewski from the National Sciences and Engineering Council (NSERC), The Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) and a grant to Susan Zabenskie from the Northern Scientific Training Program (NSTP). I would like to thank the Polar Continental Shelf Project (PCSP) for their logistical support; PCSP contribution number 019-06. Thank you to Konrad Gajewski and others for obtaining my core. Thank you to the students in the Laboratory for Paleoclimatology and Climatology for their help in the laboratory; especially LeBlanc for her analysis of the core.

References

Andrews, J.T., Webber, P.J., Nichols, H. (1979) A Late Holocene Pollen Diagram from Pangnirtung Pass, Baffin Island, N.W.T., Canada. *Review of Palaeobotany and Palynology* **27**, 1-28.

Bennett, K.D., Willis, K.J. (2001) *Pollen in: Tracking Environmental Change Using Lake Sediments. Volume 3, Terrestrial, Algal, and Siliceous Indicators.* Kluwer Academic Publishers, The Netherlands.

Bigelow, N., Brubaker, L., Edwards, M., Harrison, S., Prentice, I., Anderson, P., Andreev, A., Bartlein, P., Christensen, T., Cramer, W., Kaplan, J., Lozhkin, A., Matveyeva, N., Murray, D., McGuire, A., Razzhiven, V., Ritchie, J., Smith, B., Walker, D., Gajewski, K., Wolf, V., Holmqvist, B., Igarashi, Y., Kremenetskii, K., Paus, A., Pisaric M., and Volkova, V. (2003) Climate change and Arctic ecosystems 1. Vegetation changes north of 55°N between the last glacial maximum, mid-Holocene and present. *Journal of Geophysical Research.* 108 (D19) 8170 doi: 10.1029/2002JD002558.

Bliss, L.C. (1998) *Arctic Tundra and Polar Desert Biome in North American Terrestrial Vegetation.* Cambridge University Press, Cambridge.

Cwynar, L., Burdern E., and McAndrews, J.H. (1979) An inexpensive sieving method for concentrating pollen and spores from fine-grained sediments. *Canadian Journal of Earth and Sciences* **16**, 1115-1120.

Dyke, A.S. (1984) *Quaternary geology of Boothia Peninsula and northern District of Keewatin, central Canadian Arctic, Memoir 407.* Ottawa: Geological Survey of Canada

Faegri, K. and Iverson, J. (1975) *Textbook of Pollen Analysis*. 3rd ed. New York: Hafner Press. 295 pp.

Federova, I.T., Volkava, Y.A., Varlyguin, E. (1994) World vegetation cover. Digital raster data on a 30-minute cargesian orthonormal geodetic (lat/long) 1080 x 2160 grid. *In: Global Ecosystems Database Version 2.0. USDOC/NOAA* National Geophysical Data Center, Boulder, CO.Fredskild, B. (1973) Studies in the Vegetational History of Greenland. *Meddelelser om Gronlond* **198** (4), 1-245.

Gajewski, K. (1995) Modern and Holocene Pollen Assemblages from Some Small Arctic Lakes on Somerset Island, NWT, Canada. *Quaternary Research* **44**, 228-237.

Gajewski, K. (2002) Modern Pollen Assemblages in Lake Sediments from the Canadian Arctic. *Arctic, AntArctic, and Alpine Research* **34,** (1), 26-32.

Gajewski, K. & Atkinson, D. (2003) Climate Change in Northern Canada. *Environmental Reviews* **11,** 69-102.

Gajewski, K., Frappier, M. (1995) A Holocene Lacustrine record of Environmental Change in Northeast Prince of Wales Island, Nunavut, Canada. *Boreas* **30**, 285-89.

Gajewski, K., Garneau, M., Bourgeois, J. (1995) Paleoenvironments of the Canadian High Arctic Derived from Pollen and Plant Macrofossils: Problems and Potentials. *Quaternary Science Reviews* **14**, 609-625.

Gajewski, K., Mott, R.J., Ritchie, J.C., Hadden, K. (2000) Holocene Vegetation History of Banks Island, Northwest Territories, Canada. *Canadian Journal of Botany* **78**, 430-436.

Hyvarinen, H. (1985) Holocene Pollen Stratigraphy of Baird Inlet, East-Central Ellesmere Island, Arctic Canada. *Boreas* **14**, 19-32.

Kapp, R. (2000) *Pollen and Spores*. 2nd Ed. American Association of Stratigraphic Palynologists Foundation Publication. 279 pp.

Kerwin, M.W., Overpeck, J.T., Webb, R.S., Anderson, K.H. (2004) Pollen-based Summer Temperature Reconstructions for the Eastern Canadian Boreal Forest, SubArctic and Arctic. *Quaternary Science Review* **23**, 1901-1924.

Kauffman, D., Ager, TA., Anderson, NJ., Anderson, PM., Andrews, JT., Bartlein, PJ., Brubaker, LB., Coats, LL., Cwynar, LC., Duvall, ML., Dyke, AS., Edwards, ME., Eisner, WR., Gajewski, K., Geirsdóttir, A., Hu, FS., Jennings, AE., Kaplan, MR., Kerwin, MW., Lozhkin, AV., MacDonald, GM., Miller, GH., Mock, CJ., Oswald, WW., Otto-Bliesner, BL., Porinchu, DF., Rühland, K., Smol, JP., Steig, EJ., and Wolfe BB (PARCS working group) (2004). Holocene thermal maximum in the western Arctic (0° to 180°W). *Quaternary Science Reviews* **23**, 529-560.

LeBlanc, M. (2002) *A diatom-based Holocene palaeoenvironmental record from a mid-Arctic lake on Boothia Peninsula, central mid Arctic, Nunavut, Canada.* MSc Thesis, University of Ottawa, Ottawa, Canada.

LeBlanc, M., Gajewski, K., Hamilton, P.B. (2004) A diatom-based Holocene palaeoenvironmental record from a mid-Arctic lake on Boothia Peninsula, Nunavut, Canada. *The Holocene* **14**, 417-425.

McAndrews, J.H., Berti, A.A. and Norris, G. (1973) *Key to the Quaternary pollen and spores of the Great Lakes region.* Royal Ontario Museum Miscellaneous Publication.

Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Case, R., Douglas, M., Finney, B., Gajewski, K., Jacoby, S., Jennings, A., Lamoureux, S., Lasca, A., MacDonald, G., Moore, J., Retelle, M., Smith, S., Wolfe, A., Zielinski, G. (1997) Arctic Environmental Change of the Last Four Centuries. *Science* **278**, 1251-1256.

Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Bertrand, C. J. H., Blackwell, P. G., Buck, C. E., Burr, G. S., Cutler, K. B., Damon, P. E., Edwards, R. L., Fairbanks, R. G., Friedrich, M., Guilderson, T. P., Hogg, A. G., Hughen, K. A., Kromer, B., McCormac, F. G., Manning, S. W., Ramsey, C. B., Reimer, R. W., Remmele, S., Southon, J. R., Stuiver, M., Talamo, S., Taylor, F. W., van der Plicht, J., and Weyhenmeyer, C. E. 2004a. IntCal04 Terrestrial radiocarbon age calibration, 26 - 0 ka BP. Radiocarbon 46, 1029-1058.

Ritchie, J.C., Cwynar, L.C., and Spear, R.W. (1983) Evidence from North-West Canada for an Early Holocene Milankovitch Thermal Maximum. *Nature* **305**, 126-128.

Sawada, M. (2006) An open source implementation of the Modern Analog Technique (MAT) within the R computing environment. *Computers and Geosciences* **32**, 818-833.

Seppa, H., Cwynar, L.C., Macdonald, G.M. (2003) Post-glacial Vegetation reconstruction and a possible 8200 cal. yr BP Event from the Low Arctic of Continental Nunavut, Canada. *Journal of Quaternary Science* **18**, 621-629.

Short, S.K., Andrews, J.T., Mode, W.N. (1989) Modern and Late Quaternary Pollen Spectra of Fiord Sediments, Eastern Baffin Island, Arctic Canada. *Marine Micropaleontology*. **15**, 181-202.

Whitmore, J., Gajewski, K., Sawada, M., Williams, J.W., Minckley, T., Shuman, B., Bartlein, P.J., Webb III, T., Viau, A.E., Shafer, S., Anderson, P. & Brubaker, L.B. (2005) A North American Modern Pollen Database for Multi-scale Paleoecological and Paleoclimatic Applications. *Quaternary Science Reviews*

Wolfe, A.P., Fréchette, B., Richard, P.J.H., Miller, G.H., Forman, S.L. (2000) Paleoecology of a > 90,000-year Lacustrine Sequence from Fog Lake, Baffin Island, Arctic Canada. *Quaternary Science Reviews* **19**, 1677-1699.

Zabenskie, S. (2006) *Post-Glacial Climatic Change on Boothia Peninsula, Nunavut, Canada.* MSc Thesis, University of Ottawa, Ottawa, Canada.

CHAPTER 5 - CONCLUSION

A pollen diagram from Lake JR01 (69°54'N, 95°4.2'W, 120 m.a.s.l.) from the Boothia Peninsula documents the post-glacial climate and vegetation history of the region. Pollen percentages in Lake JR01 did not change much during the past 7200 years nevertheless, the subtle changes that do occur suggest climate impacts on the regional vegetation. Major local pollen occurring in Lake JR01 are Cyperaceae, Poaceae and *Salix,* with Cyperaceae pollen percentages accounting for over 50% of the pollen in the early and late part of the core. Higher pollen percentages of Cyperaceae and *Salix* were interpreted as warmer temperatures. Cooler temperatures were interpreted by increases in pollen percentages of high-Arctic pollen such as Poaceae and Brassicaceae (Gajewski 2002). The high percentages of Cyperaceae throughout the core indicate that the regional vegetation remained middle-Arctic, with periods of cooler temperatures indicated by increases of Poaceae pollen.

Long-distance pollen included *Pinus, Alnus, Betula,* and *Picea,* with *Pinus* accounting for 30% of the pollen in the middle to late Holocene. In general as *Picea, Alnus*, and *Betula* pollen percentages increased, those of *Pinus* decreased. Increases in long-distance pollen were interpreted as warmer temperatures because the transport of these should increase with stronger southerly winds.

Temperatures were cooler in the early part of the core and the late Holocene, with warmer temperatures interpreted for the middle-Holocene and in the last 30 years. Evidence for this comes not only by the changes in the pollen percentages and concentrations, but also by the changes in the organic matter in the core as well.

Diatoms had previously been analyzed in this core. Interpretation of the diatom stratigraphy indicated a significant warming in the middle-Holocene around 5800 cal yr BP and cooling in the late Holocene. This corresponds well with the interpretation and quantitative reconstruction presented in this study.

Several studies (Somerset Island (Gajewski 1995), Prince of Wales Island (Gajewski and Frappier 2001), Baffin Island (Short et al 1989), Banks Island (Gajewski et al 2000) and the low-Arctic Nunavut (TK-2; Seppa et al 2003)) showed an early to middle-Holocene warming and cooling in the late-Holocene. Similar results were shown here. The timing of the climate change is better constrained in this study as the dating and pollen analysis were performed at higher resolutions than previous studies.

In this study I attempted to quantitatively reconstruct July temperatures, and it varied between 6.3-7.8°C at the site. However, more surface samples are needed to make a more reliable estimate of temperatures from the Arctic.

Pollen reconstruction is a difficult process because counting pollen is so time consuming. With the use of a heavy liquid process for concentrating the pollen from the sediment matrix introduced in this study, I was able to perform a high-resolution study of the pollen (the highest yet available in the Canadian Arctic). Use of this processing method will enable future researchers to prepare more pollen profiles at higher resolutions.

References

Anderson, P.M., Bartlein, P.J., Brubaker, L.B., Gajewski, K. and Ritchie, J.C. (1989) Modern Analogs of late-Quaternary pollen spectra from the western interior of North America. *Journal of Biogeography* **16**, 573-596.

Anderson, P.M., Bartlein, P.J., Brubaker, L.B., Gajewski, K. and Ritchie, J.C. (1989) Vegetation-pollen-climate relationships for the arcto-boreal region of North America and Greenland. *Journal of Biogeography* **18**, 565-582.

Andrews, J.T., Webber, P.J., Nichols, H. (1979) A Late Holocene Pollen Diagram from Pangnirtung Pass, Baffin Island, N.W.T., Canada. *Review of Palaeobotany and Palynology* **27**, 1-28.

Appleby, P.G. (2001) *Chronostratigraphic Techniques in Recent Sediments in: Tracking Environmental Change Using Lake Sediments. Volume 1, Basin Analysis, Coring, and Chronological Techniques.* Kluwer Academic Publishers, The Netherlands.

Barry, R.G., Elliott, D.L., Crane, R.G. (1981) The Palaeoclimatic Interpretation of Exotic Pollen Peaks in Holocene Records from the Eastern Canadian Arctic: A Discussion. *Review of Palaeobotany and Palynology* **33**, 153-167.

Bartlein, P.J., Edwards, M.E., Shafer, S.L., Barker Jr., E.D. (1995) Calibration of Radiocarbon Ages and the Interpretation of Paleoenvironmental Records. *Quaternary Research* **44**, 417-424.

Bay, C., Fredskild, B. (1997) Present and Past Vegetation in the High Arctic, Easternmost North Greenland and the Relation to the Northeast Water Polyna. *Journal of Marine Systems* **10**, 35-39.

Bennett, K.D., Willis, K.J. (2001) *Pollen in: Tracking Environmental Change Using Lake Sediments. Volume 3, Terrestrial, Algal, and Siliceous Indicators.* Kluwer Academic Publishers, The Netherlands.

Bigelow, N., Brubaker, L., Edwards, M., Harrison, S., Prentice, I., Anderson, P., Andreev, A., Bartlein, P., Christensen, T., Cramer, W., Kaplan, J., Lozhkin, A., Matveyeva, N., Murray, D., McGuire, A., Razzhiven, V., Ritchie, J., Smith, B., Walker, D., Gajewski, K., Wolf, V., Holmqvist, B., Igarashi, Y., Kremenetskii, K., Paus, A., Pisaric M., and Volkova, V. (2003) Climate change and Arctic ecosystems 1. Vegetation changes north of 55°N between the last glacial maximum, mid-Holocene and present. *Journal of Geophysical Research.* 108 (D19) 8170 doi: 10.1029/2002JD002558.

Birks, H.J.B. and Birks, H.H. (1980) *Quaternary Palaeoecology*. Botany School, University of Cambridge. Edward Arnold.

Bjorck, S. (2001) ^{14} *C Chronostratigraphic Techniques in Paleolimnology in: Tracking Environmental Change Using Lake Sediments. Volume 1, Basin Analysis, Coring, and Chronological Techniques.* Kluwer Academic Publishers, The Netherlands.

Bliss, L.C. (1998) *Arctic Tundra and Polar Desert Biome in North American Terrestrial Vegetation*. Cambridge University Press, Cambridge.

Bolch, C.J.S. (1997) The use of sodium polytungstate for the separation and concentration of living dinoflagellate cysts from marine sediments. *Phycologia* **36**, 472-478.

Bourgeois, J.C., Koerner, R.M., Gajewski, K., Fisher, D.A. (2000) A Holocene Ice-Core Pollen Record from Ellesmere Island, Nunavut, Canada. *Quaternary Research* **54**, 275-283.

Boyle, J.F. (2001) *Inorganic Geochemical Methods in Palaeolimnology in: Tracking Environmental Change Using Lake Sediments. Volume 2, Physical and Geochemical Methods.* Kluwer Academic Publishers, The Netherlands.

Cwynar, L., Burdern E., and McAndrews, J.H. (1979) An inexpensive sieving method for concentrating pollen and spores from fine-grained sediments. *Canadian Journal of Earth and Sciences* **16**, 1115-1120.

Dean Jr., W.E. (1974) Determination of Carbonate and Organic Matter in Calcareous Sediments and Sedimentary Rocks by Loss on Ignition: Comparison with Other Methods. *Journal of Sedimentary Petrology* **44**, 242-248.

Dyke, A.S. (1984) *Quaternary geology of Boothia Peninsula and northern District of Keewatin, central Canadian Arctic, Memoir 407.* Ottawa: Geological Survey of Canada

Faegri, K. and Iverson, J. (1975) *Textbook of Pollen Analysis*. 3rd ed. New York: Hafner Press. 295 pp.

Federova, I.T., Volkava, Y.A., Varlyguin, E. (1994) World vegetation cover. Digital raster data on a 30-minute cargesian orthonormal geodetic (lat/long) 1080 x 2160 grid. *In: Global Ecosystems Database Version 2.0. USDOC/NOAA* National Geophysical Data Center, Boulder, CO.Fredskild, B. (1973) Studies in the Vegetational History of Greenland. *Meddelelser om Gronlond* **198** (4), 1-245.

Fredskild, B. (1973) Studies in the Vegetational History of Greenland. *Meddelelser om Grønland* **198** (4), 1-245.

Gajewski, K. (1995) Modern and Holocene Pollen Assemblages from Some Small Arctic Lakes on Somerset Island, NWT, Canada. *Quaternary Research* **44**, 228-237.

Gajewski, K. (2002) Modern Pollen Assemblages in Lake Sediments from the Canadian Arctic. *Arctic, AntArctic, and Alpine Research* **34,** No. 1, 26-32.

Gajewski, K (n.d.) Laboratory for Paleoclimatology and Climatology website http://www.lpc.uottawa.ca/resources/protocols.html

Gajewski, K. & Atkinson, D. (2003) Climate Change in Northern Canada. *Environmental Reviews* **11,** 69-102.

Gajewski, K., Frappier, M. (1995) A Holocene Lacustrine record of Environmental Change in Northeast Prince of Wales Island, Nunavut, Canada. *Boreas* **30**, 285-89.

Gajewski, K., Garneau, M., Bourgeois, J. (1995) Paleoenvironments of the Canadian High Arctic Derived from Pollen and Plant Macrofossils: Problems and Potentials. *Quaternary Science Reviews* **14**, 609-625.

Gajewski, K., Mott, R.J., Ritchie, J.C., Hadden, K. (2000) Holocene Vegetation History of Banks Island, Northwest Territories, Canada. *Canadian Journal of Botany* **78**, 430-436.

Glew, J.R. (1991) Miniature gravity corer for recovering short sediment cores. *Journal of Paleolimnology* **5**, 285-287.

Hyvarinen, H. (1985) Holocene Pollen Stratigraphy of Baird Inlet, East-Central Ellesmere Island, Arctic Canada. *Boreas* **14**, 19-32.

Kapp, R. (2000) *Pollen and Spores*. 2nd Ed. American Association of Stratigraphic Palynologists Foundation Publication. 279 pp.

Kerwin, M.W., Overpeck, J.T., Webb, R.S., Anderson, K.H. (2004) Pollen-based Summer Temperature Reconstructions for the Eastern Canadian Boreal Forest, SubArctic and Arctic. *Quaternary Science Review* **23**, 1901-1924.

Kauffman, D., Ager, TA., Anderson, NJ., Anderson, PM., Andrews, JT., Bartlein, PJ., Brubaker, LB., Coats, LL., Cwynar, LC., Duvall, ML., Dyke, AS., Edwards, ME., Eisner, WR., Gajewski, K., Geirsdóttir, A., Hu, FS., Jennings, AE., Kaplan, MR., Kerwin, MW., Lozhkin, AV., MacDonald, GM., Miller, GH., Mock, CJ., Oswald, WW., Otto-Bliesner, BL., Porinchu, DF., Rühland, K.,

Smol, JP., Steig, EJ., and Wolfe BB (PARCS working group) (2004). Holocene thermal maximum in the western Arctic (0° to 180°W). *Quaternary Science Reviews* **23**, 529-560.

LeBlanc, M. (2002) *A diatom-based Holocene palaeoenvironmental record from a mid-Arctic lake on Boothia Peninsula, central mid Arctic, Nunavut, Canada.* MSc Thesis, University of Ottawa, Ottawa, Canada.

LeBlanc, M., Gajewski, K., Hamilton, P.B. (2004) A diatom-based Holocene palaeoenvironmental record from a mid-Arctic lake on Boothia Peninsula, Nunavut, Canada. *The Holocene* **14**, 417-425.

MacDonald, G.M., Beukens, R.P., Kieser, W.E. (1991) Radiocarbon Dating of Limnic Sediments: A Comparative Analysis and Discussion. *Ecology* **72**, 1150-1155.

Maxwell, J.B. (1982) *The Climate of the Canadian Arctic Islands and Adjacent Waters. Volume 2.* Atmospheric Environment Service. Minister of Supply and Services.

McAndrews, J.H., Berti, A.A. and Norris, G. (1973) *Key to the Quaternary pollen and spores of the Great Lakes region.* Royal Ontario Museum Miscellaneous Publication.

Munsterman, D. and Kerstholt, S. (1995) Sodium polytungstate, a new non-toxic alternative to bromofrom in heavy liquid separation. *Elsevier* **91**, 417-422.

Nichols, H. (1967) The Disturbance of Arctic Lake Sediments by 'Bottom Ice': A Hazard for Palynology. *Arctic* **20**, 213-214.

Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Case, R., Douglas, M., Finney, B., Gajewski, K., Jacoby, S., Jennings, A., Lamoureux, S., Lasca, A., MacDonald, G., Moore, J., Retelle, M., Smith, S., Wolfe, A., Zielinski, G. (1997) Arctic Environmental Change of the Last Four Centuries. *Science* **278**, 1251-1256.

Overpeck, J., Webb III, T., Prentice, I.C. (1985) Quantitative interpretation of fossil pollen spectra: Dissimilarity coefficients and the method of modern analogs. *Quaternary Research* **23,** 87-108.

Porsild, A.E. (1955) *The Vascular Plants of the Western Canadian Arctic Archipelago. Bulletin No.135.* National Museum of Canada, Department of Northern Affairs and National Resources.

Porsild, A.E. (1964) *Illustrated Flora of the Canadian Arctic Archipelago. Bulletin No.146.* National Museum of Canada, Department of Northern Affairs and National Resources.

Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Bertrand, C. J. H., Blackwell, P. G., Buck, C. E., Burr, G. S., Cutler, K. B., Damon, P. E., Edwards, R. L., Fairbanks, R. G., Friedrich, M., Guilderson, T. P., Hogg, A. G., Hughen, K. A., Kromer, B., McCormac, F. G., Manning, S. W., Ramsey, C. B., Reimer, R. W., Remmele, S., Southon, J. R., Stuiver, M., Talamo, S., Taylor, F. W., van der Plicht, J., and Weyhenmeyer, C. E. 2004a. IntCal04 Terrestrial radiocarbon age calibration, 26 - 0 ka BP. Radiocarbon 46, 1029-1058.

Ritchie, J.C., Cwynar, L.C., and Spear, R. W. (1983) Evidence from North-West Canada for an Early Holocene Milankovitch Thermal Maximum. *Nature* **305**, 126-128.

Sandgren, P., Snowball, I. (2001) *Application of Mineral Magnetic Techniques to Paleolimnology in: Tracking Environmental Change Using Lake Sediments. Volume 2, Physical and Geochemical Methods.* Kluwer Academic Publishers, The Netherlands.

Sawada, M. (2006) An open source implementation of the Modern Analog Technique (MAT) within the R computing environment. *Computers and Geosciences* **32**, 818-833.

Seppa, H., Cwynar, L.C., Macdonald, G.M. (2003) Post-glacial Vegetation reconstruction and a possible 8200 cal. yr BP Event from the Low Arctic of Continental Nunavut, Canada. *Journal of Quaternary Science* **18**, 621-629.

Short, S.K., Andrews, J.T., Mode, W.N. (1989) Modern and Late Quaternary Pollen Spectra of Fiord Sediments, Eastern Baffin Island, Arctic Canada. *Marine Micropaleontology*. **15**, 181-202.

Skipp, G.L., Brownfield, I. (1993) Improved density gradient separation techniques using Sodium Polytungstate and a comparison to the use of other heavy liquids. *U.S. Geological Survey*, Open-File report 92-386.

Stockmarr, J. (1971) Tablets with spores used in absolute pollen analysis. *Pollen et Spores* **13**, 615-621

Takeshi, N., Brugiapaglia, E., Digerfeldt, G., Reille, M., De Beaulieu, J., Yasuda, Y. (1998) Dense-media separation as a more efficient pollen extraction method for use with organic sediment/deposit samples: comparison with the conventional method. *Boreas* **27** 15-24.

Traverse, A. (1988) *Paleopalynology*. Unwin Allen, Boston.

Torresan, M. (1987) The use of sodium polytungstate in heavy mineral separations. *U.S. Geological Survey*, Open-File Report 87-590.

Wagner, B., Melles, M., Hahne, J., Niessen, F., Hubberten, H. (2000) Holocene Climate History of Geographical Society Ø, East Greenland – Evidence from Lake Sediments. *Palaeogeography, Palaeoclimatology, Palaeoecology* **160**, 45-68.

Whitmore, J., Gajewski, K., Sawada, M., Williams, J.W., Minckley, T., Shuman, B., Bartlein, P.J., Webb III, T, Viau, A.E., Shafer, S., Anderson, P. & Brubaker, L.B. (2005) A North American Modern Pollen Database for Multi-scale Paleoecological and Paleoclimatic Applications. *Quaternary Science Reviews* **24**, 1828-1848.

Wolfe, A.P., Fréchette, B., Richard, P.J.H., Miller, G.H., Forman, S.L. (2000) Paleoecology of a > 90,000-year Lacustrine Sequence from Fog Lake, Baffin Island, Arctic Canada. *Quaternary Science Reviews* **19**, 1677-1699.

Zolitschka, B. et al (2001) ^{14} *C Chronostratigraphic Techniques in Paleolimnology in: Tracking Environmental Change Using Lake Sediments. Volume 1, Basin Analysis, Coring, and Chronological Techniques.* Kluwer Academic Publishers, The Netherlands.

Appendix 5: Pollen taxa retained for analyses of PCA and MAT.

A. For the PCA and second reconstruction of the MAT, sites classified as "Arctic" (Federova et al 1994) were retained and only local and regional pollen were included in the analysis. Pollen types retained for this analysis included: Apiaceae, *Artemisia*, *Betula*, *Botrychium*, Brassicaceae, Campanulaceae, Caryophyllaceae, Chenopodiaceae, Cichorioideae, Cyperaceae, *Dryas*, Elaeaganaceae, *Equisetum*, Ericaceae, Fabaceae, Lycopodiaceae, *Myrica, Papaver, Pedicularis,* Plantaginaceae, Poaceae, *Polygonum viviparum, Polypodium, Potentilla, Pteridium*, Ranunculaceae, Rosaceae, *Rubus*, *Rumex/Oxyria, Salix, Saxifraga cernua, S. hieracifolia, S. oppositifolia, S. tricuspidata,* other Saxifragaceae, Scrophulariaceae, *Thalictrum and* Tubuliflorae.

B. For the first MAT reconstruction, sites classified as "Arctic" and "Forest-tundra" according to Federova et al (1994) and local and regional and long-distance pollen were retained for this analysis. Pollen types retained included: *Abies*, Acer, *Alnus, Amorpha*, Anacardiaceae, Apiaceae, Aquifoliaceae, *Arceuthobium, Armeria, Artemisia*, Cichorioideae, *Betula*, Boraginaceae, *Botrychium*, Brassicaceae, Caprifoliaceae, *Carya*, Caryophyllaceae, *Castanea, Celtis, Cephalanthus, Cercocarpus*, Chenopodiaceae, Compositae (*Iva, Ambrosia, Xanthium*), *Cornus, Corylus*, Cupressaceae, Cyperaceae, *Dryas*, Elaeaganaceae, *Ephedra, Equisetum*, Ericales, *Eriogonum,* Fabaceae, *Fagus, Fraxinus, Juglans, Koenigia islandica*, Lamiaceae, *Larix*, Liliaceae, *Liquidambar*, *Lycopodium*, Moraceae, Myricaceae, *Nyssa*, Onagraceae, Osmundaceae, *Ostrya, Papaver, Pedicularis, Picea, Pinus*, Plantaganaceae, *Platanus*, Poaceae, Polemoniaceae, *Polygonum, P.bistortoides*, Polypodiaceae, *Populus, Potentilla, Pteridium, Quercus*,

Ranunculaceae, Rhamnaceae, Rosaceae, Rubiaceae, *Rubus, Rumex/Oxyria, Salix, Sanguisorba, Sarcobatus,* Saxifragaceae, *S. cernua, S.hieracifolia, S.oppositifolia, S.tricuspidata,* Scrophulariaceae, *Selaginella, Shepherdia, Sphagnum, Taxus, Thalictrum, Tilia, Tsuga, Ulmus,* and Urticaceae.

Appendix 2: Pollen counts for Lake JR01

Cal yr BP	Depth	*Picea* 1/1	*Picea* 1/2	*Abies*	*P.diploxylon*	*P.haploxylon*	*P.undiff*	*Pinus* 1/2	Larix	Cupressaceae	Betula
9	0	12	0	0	17	0	30	0	0	0	9
23	1	6	12	0	28	0	31	50	0	0	7
28	2	15	12	0	46	0	51	74	0	0	12
33	2	11	5	0	41	0	29	57	0	0	6
36	3	11	41	1	26	0	7	53	0	0	8
74	4	10	26	0	30	0	22	56	0	0	11
132	7	12	26	0	26	0	26	38	0	0	11
215	9	10	15	0	34	0	12	60	0	0	8
307	11	9	32	0	34	0	21	75	0	0	0
399	13	2	36	0	28	0	12	53	0	1	6
491	15	8	21	0	22	0	20	67	0	1	12
584	17	9	24	0	25	0	33	90	0	0	4
676	19	11	20	0	19	0	21	53	0	0	8
803	22	12	31	0	10	0	24	19	0	1	20
987	26	10	28	0	18	0	36	50	0	1	15
1172	30	24	16	0	29	0	23	50	0	0	2
1310	34	4	10	0	7	0	23	19	0	0	6
1638	44	11	22	0	31	0	29	49	0	0	9
1900	52	19	10	0	16	0	35	52	0	0	12
2162	61	12	12	0	26	0	24	41	0	0	6
2256	70	12	24	0	25	0	25	56	0	0	8
2517	95	16	20	0	22	0	32	44	0	0	2
2684	109	21	22	0	16	0	24	34	0	0	17
3045	139	9	15	0	9	0	14	15	0	0	9
3105	144	17	32	0	9	0	21	54	0	0	12
3231	154	17	26	0	25	0	30	46	0	0	7
3402	161	15	51	1	23	0	15	60	0	0	6
3475	164	21	27	2	7	0	35	79	0	1	9
3596	169	7	12	0	11	0	31	47	0	0	13
3718	174	10	37	1	15	0	16	37	0	0	12
3791	177	17	10	0	13	0	19	64	0	0	10
3840	179	12	45	0	18	0	10	47	0	1	13
3888	181	11	20	0	12	0	26	51	0	0	7
3961	184	17	21	0	12	1	25	23	0	1	10
4010	186	17	24	0	15	0	18	53	0	0	19
4083	189	22	41	1	8	0	25	56	0	3	19
4156	192	15	21	0	12	0	26	45	0	1	18
4205	194	26	47	2	32	0	45	119	0	0	32
4302	198	21	39	0	26	0	20	77	0	0	7
4448	204	18	21	0	22	0	25	45	0	0	19
4570	209	21	73	0	26	0	15	51	0	0	15
4692	214	15	30	0	7	0	7	47	0	0	7
4962	231	21	40	0	10	0	23	31	0	0	24
4994	234	11	30	0	9	0	11	53	0	0	18
5154	249	4	31	0	3	0	7	20	0	0	15
5261	259	14	80	0	14	0	6	24	0	0	9
5475	279	21	23	0	17	0	20	36	0	0	25
5582	289	17	17	1	10	0	17	17	0	0	31
5676	319	11	15	0	4	0	16	21	0	0	40
5697	339	27	36	2	10	0	16	59	0	0	45
5719	359	9	11	0	3	0	12	9	1	1	24
5751	389	9	21	0	11	0	6	22	0	0	25
5836	399	6	10	1	3	0	9	7	0	0	21
6060	409	21	29	0	6	0	9	25	0	0	24
6396	424	7	14	0	3	0	11	9	0	0	34
6732	439	11	41	1	9	0	12	23	0	0	21
6956	449	12	5	0	4	0	12	12	0	0	43
7096	469	8	18	0	3	1	12	12	0	0	11

Cal yr BP	*Populus*	*Juglans*	*Ostrya*	*Tsuga*	*A. crispa*	*A. rugosa*	*Salix*	*Corylus*	*Cornus*	*Ulmus*	*Myrica*	Ericaceae	Cassiope
9	0	1	0	0	3	0	26	0	0	0	0	0	2
23	0	0	0	0	6	0	17	0	0	0	0	0	2
28	0	0	0	0	8	0	18	0	1	0	0	0	1
33	0	0	0	0	6	0	10	0	0	0	0	0	1
36	0	0	0	0	10	0	8	0	0	0	0	1	0
74	0	0	0	0	11	0	3	0	1	0	0	0	1
132	0	0	0	0	10	0	4	0	0	0	0	0	2
215	0	0	0	0	11	1	3	0	0	0	0	0	0
307	0	0	0	0	10	0	2	0	0	0	0	0	1
399	0	0	0	0	1	0	6	0	0	0	0	0	1
491	0	0	0	0	13	0	7	0	0	0	0	0	1
584	0	0	0	0	3	0	6	0	0	0	0	0	2
676	0	0	0	0	10	0	5	0	0	0	0	0	1
803	2	0	0	1	14	2	12	0	0	0	0	0	0
987	0	0	0	0	23	0	4	0	1	0	0	0	3
1172	0	0	0	0	8	0	3	0	0	0	0	0	1
1310	0	0	0	0	6	0	2	0	0	0	0	0	0
1638	1	0	0	0	9	0	4	0	0	0	0	0	1
1900	1	0	0	0	12	0	7	0	0	0	0	0	2
2162	0	0	0	0	12	0	5	0	0	0	0	0	2
2256	0	0	0	0	11	0	3	0	0	0	0	0	1
2517	0	0	0	0	9	0	6	0	0	0	0	0	1
2684	1	0	0	0	17	0	15	0	0	0	0	0	2
3045	1	0	0	0	6	0	0	0	0	0	0	0	1
3105	0	0	0	0	6	1	5	0	0	0	0	0	1
3231	0	0	0	0	11	0	3	0	0	0	0	1	0
3402	0	0	0	0	8	0	5	0	0	0	0	0	2
3475	0	0	0	0	17	1	5	0	0	0	0	0	0
3596	0	0	0	0	18	0	9	0	0	0	0	0	0
3718	0	0	0	0	8	0	3	0	0	0	0	0	1
3791	0	0	0	0	10	0	1	0	0	0	0	1	1
3840	0	0	0	0	8	0	6	0	1	0	0	0	0
3888	0	0	0	0	14	0	0	0	1	0	0	0	0
3961	0	0	0	0	7	4	2	0	0	0	0	0	0
4010	0	0	0	0	15	0	5	0	0	0	0	0	1
4083	0	0	2	0	13	2	14	1	1	0	0	0	3
4156	0	0	0	0	11	0	11	0	0	0	0	0	1
4205	1	0	0	0	43	0	14	0	0	0	0	0	5
4302	0	0	0	0	9	0	10	0	0	0	0	0	0
4448	1	0	0	0	11	0	3	0	0	0	0	0	1
4570	0	0	0	0	14	0	5	0	0	0	0	1	2
4692	0	0	0	0	7	0	1	0	0	0	0	0	0
4962	2	0	0	0	18	0	1	0	0	0	0	0	1
4994	0	0	0	0	7	0	7	0	0	0	0	0	1
5154	0	0	0	0	16	5	9	0	0	0	0	0	0
5261	0	0	0	0	10	0	3	0	0	0	0	0	1
5475	0	0	0	0	17	0	2	0	0	0	0	0	1
5582	1	0	0	0	35	0	16	0	1	0	0	0	0
5676	0	0	0	0	28	2	6	0	1	0	0	0	0
5697	0	0	0	0	40	1	13	0	1	1	0	0	1
5719	0	0	0	0	22	4	19	0	0	0	0	0	2
5751	0	0	0	0	29	0	5	0	0	0	0	0	1
5836	0	0	0	0	35	2	16	0	1	0	0	0	0
6060	0	0	0	0	24	0	7	0	0	0	0	0	0
6396	0	0	0	0	25	2	11	0	0	0	0	0	1
6732	0	0	0	0	32	0	7	0	0	0	0	0	0
6956	0	0	0	0	43	1	13	0	0	0	0	0	0
7096	0	0	2	0	11	5	13	1	0	0	1	0	0

Cal yr BP	Caryophyllaceae	Chenopodiaceae	Asteraceae	*Artemisia*	*Ambrosia*	Brassicaceae	Cyperaceae	Poaceae	Fabaceae
9	1	0	0	*1*	*0*	1	176	12	1
23	1	0	1	2	0	4	159	11	0
28	1	1	0	4	0	1	182	8	0
33	1	0	3	1	1	1	132	3	0
36	2	1	1	9	2	5	77	2	0
74	1	0	0	16	1	2	72	12	0
132	0	0	0	7	1	4	98	2	0
215	1	0	0	3	0	4	89	1	0
307	0	0	0	7	1	2	78	5	0
399	2	0	1	6	0	1	87	5	0
491	2	1	2	9	1	2	73	1	0
584	2	0	0	5	0	1	90	5	0
676	2	0	0	12	0	2	87	1	1
803	0	0	0	2	2	0	137	5	0
987	1	0	0	8	0	1	87	5	1
1172	0	0	0	5	0	0	105	5	0
1310	1	0	2	1	0	2	47	3	0
1638	1	1	2	13	0	1	80	5	0
1900	0	0	2	9	0	5	99	8	1
2162	4	0	1	4	2	5	90	12	0
2256	1	0	1	6	0	2	96	2	0
2517	0	1	0	11	0	1	121	7	0
2684	0	0	2	5	0	0	172	2	0
3045	0	0	1	9	1	0	95	5	0
3105	0	0	3	3	0	0	128	7	0
3231	0	1	0	4	0	0	119	4	0
3402	0	0	0	5	0	0	127	6	0
3475	1	0	2	6	0	0	149	10	0
3596	1	1	3	14	0	0	135	7	0
3718	1	1	0	7	0	0	174	10	0
3791	1	0	1	4	0	0	99	0	1
3840	0	0	2	6	0	0	98	1	0
3888	0	0	1	9	0	0	133	10	0
3961	1	0	0	7	3	0	156	2	1
4010	0	0	1	5	0	0	120	2	0
4083	0	0	3	12	1	0	211	7	0
4156	1	0	1	14	0	0	121	6	0
4205	1	0	6	30	1	3	292	10	0
4302	1	0	0	3	1	3	193	11	0
4448	0	1	2	1	0	1	117	8	0
4570	1	1	2	4	0	6	134	3	0
4692	2	1	2	0	1	0	126	5	0
4962	2	0	0	2	0	1	100	5	1
4994	1	0	2	7	0	1	112	1	0
5154	0	0	1	7	2	0	186	4	0
5261	1	1	0	10	2	0	125	3	0
5475	0	0	1	2	0	0	142	7	0
5582	0	1	1	9	0	0	186	8	0
5676	0	1	6	6	0	1	198	4	0
5697	0	5	1	9	2	2	317	7	0
5719	0	0	1	15	0	0	234	11	1
5751	0	1	1	10	1	1	106	9	1
5836	0	2	3	10	0	0	182	4	0
6060	0	0	1	4	0	2	171	6	0
6396	0	1	1	6	0	0	172	4	0
6732	1	0	1	8	0	1	156	2	1
6956	0	1	1	10	0	1	151	4	0
7096	1	0	2	14	1	0	198	6	0

Cal yr BP	*Oxyria*	*Plantago*	*P.viviparum*	Ranunculaceae	Papaver	Rosaceae	*Potentilla*	*Dyras*	*Rubus*	Saxifragaceae
9	1	0	1	0	2	3	0	3	0	2
23	1	0	0	0	0	0	0	2	0	0
28	2	0	0	1	1	1	0	0	0	0
33	0	0	0	0	1	0	0	1	0	0
36	2	0	0	0	0	0	0	1	0	0
74	3	0	0	0	2	1	0	0	0	0
132	0	0	0	0	0	0	0	0	0	0
215	1	0	0	0	0	0	0	2	0	0
307	1	1	0	0	0	1	0	3	0	0
399	1	0	0	0	1	0	0	4	1	0
491	0	0	0	0	0	0	0	2	0	0
584	0	0	0	1	0	0	0	0	0	0
676	0	0	0	0	0	0	0	3	0	0
803	0	0	0	0	0	0	0	3	0	1
987	0	0	0	0	0	1	0	7	0	0
1172	0	0	0	0	0	0	0	4	0	0
1310	0	0	0	0	0	0	0	0	0	0
1638	1	0	0	0	0	1	0	1	1	0
1900	1	0	0	0	0	0	0	1	1	0
2162	0	0	0	0	0	1	0	1	0	0
2256	3	0	0	0	0	0	0	0	0	0
2517	1	0	0	0	0	0	0	1	0	0
2684	1	0	0	1	0	0	0	0	0	0
3045	0	1	0	0	0	0	0	0	0	0
3105	0	0	0	0	0	0	0	3	0	0
3231	0	0	0	0	0	0	0	2	1	0
3402	0	0	0	1	2	1	0	1	0	0
3475	0	1	0	0	0	1	0	3	0	0
3596	0	0	0	0	0	0	1	2	0	0
3718	0	0	0	0	1	0	0	0	0	1
3791	0	0	0	0	0	1	0	0	0	0
3840	0	0	0	0	0	0	0	0	0	0
3888	0	0	1	0	0	0	0	1	0	0
3961	0	0	0	0	0	0	0	0	0	1
4010	0	0	0	0	0	0	0	3	0	0
4083	2	0	1	2	0	0	0	3	0	0
4156	0	0	1	0	0	0	0	2	0	0
4205	5	1	0	1	0	1	0	8	0	0
4302	0	0	0	0	0	0	0	1	0	0
4448	0	0	0	0	0	0	0	2	1	0
4570	1	0	0	0	2	0	0	1	0	0
4692	0	0	0	0	0	0	0	0	1	0
4962	1	0	0	0	0	0	0	1	0	0
4994	0	0	0	0	1	0	0	0	0	1
5154	0	0	0	0	0	1	0	4	0	0
5261	0	0	0	0	1	0	0	1	0	1
5475	1	0	0	0	0	0	0	1	0	0
5582	1	1	0	0	1	0	0	2	0	3
5676	0	0	1	1	0	0	0	3	0	0
5697	3	0	0	0	0	0	0	4	0	0
5719	3	0	1	0	0	1	0	3	0	0
5751	0	0	0	0	0	0	0	2	0	0
5836	1	0	0	0	0	0	0	2	1	0
6060	3	0	0	0	0	0	0	4	0	0
6396	3	0	0	0	0	0	0	1	0	0
6732	1	0	0	0	0	0	0	2	0	0
6956	5	0	1	0	0	0	0	1	0	1
7096	1	0	0	0	0	0	0	1	0	0

Cal yr BP	*S.oppositifolia*	*Lycopodium*	Polypodiaceae	Equisetum	Trilete	Sphagnum	Unknown	Unidentifiable	Potomogeten
9	1	0	0	0	1	30	0	0	0
23	4	0	3	1	24	27	0	2	0
28	2	0	2	3	20	44	0	2	0
33	1	0	2	1	15	28	0	3	0
36	4	0	2	3	12	26	0	1	0
74	7	0	3	1	14	23	0	3	0
132	5	0	2	1	15	14	0	4	0
215	1	0	4	0	11	30	0	2	0
307	1	0	1	2	6	25	0	0	0
399	2	0	4	0	13	23	0	3	0
491	8	0	1	3	36	22	0	1	0
584	1	0	2	0	15	17	0	4	0
676	1	0	3	1	14	27	0	4	0
803	0	0	1	1	8	23	0	10	0
987	5	1	3	2	6	15	0	3	0
1172	3	0	0	0	13	12	0	2	0
1310	0	0	0	0	18	9	0	1	0
1638	6	0	1	0	8	18	0	4	0
1900	5	1	0	0	10	13	0	2	0
2162	2	1	5	0	16	9	0	7	0
2256	3	0	2	1	14	12	1	4	0
2517	0	0	0	1	15	23	0	5	1
2684	1	0	1	0	13	12	0	5	0
3045	3	0	0	1	8	10	0	1	0
3105	5	1	2	3	6	14	1	6	0
3231	4	0	1	0	15	13	0	2	0
3402	6	0	1	2	12	22	0	3	0
3475	6	0	0	3	14	24	0	12	0
3596	2	1	0	1	7	19	1	4	0
3718	3	0	2	2	15	18	0	5	0
3791	3	0	5	0	0	6	9	5	0
3840	5	1	1	5	5	18	0	2	0
3888	2	0	1	1	7	14	0	3	0
3961	0	0	4	2	10	17	0	6	0
4010	1	0	0	2	14	12	0	1	0
4083	2	1	3	1	5	27	0	11	0
4156	2	1	1	0	8	4	1	3	0
4205	7	1	0	2	15	27	1	11	0
4302	4	0	0	3	6	18	0	5	0
4448	6	0	0	4	12	14	1	3	0
4570	2	0	2	5	5	12	1	7	0
4692	3	0	2	9	6	16	0	5	0
4962	3	0	0	2	10	22	0	1	0
4994	3	0	2	1	18	15	1	1	0
5154	4	0	1	0	2	15	0	6	0
5261	3	0	0	1	10	24	0	1	0
5475	0	0	0	0	9	4	0	2	0
5582	0	0	0	0	6	14	0	9	0
5676	1	0	0	0	4	8	0	3	0
5697	2	0	0	4	6	16	1	9	0
5719	1	0	2	0	0	10	0	12	0
5751	3	0	2	0	16	16	0	2	0
5836	0	0	1	0	11	10	0	8	0
6060	6	0	1	5	6	13	0	3	0
6396	2	0	0	0	7	10	0	4	0
6732	10	0	1	2	10	20	1	3	0
6956	0	0	0	1	5	13	0	5	0
7096	0	1	1	2	0	15	0	8	0

Cal yr BP	Pediastrum	Total Pollen	Total AP	Total NAP	Spores	# of Tablets	Volume cm3	Counted Spike	Pollen concentration	Total Influx
9	64	335	100	205	30	2	2	1667	2713	213
23	51	401	159	185	55	2	2	3313	2179	218
28	63	513	238	204	69	2	2	4615	2001	200
33	55	360	166	145	46	2	2	3677	1762	1410
36	80	316	166	106	43	4	2	3557	2399	1919
74	53	332	171	117	41	4	3	2492	2878	144
132	66	308	155	117	32	4	3	3415	1948	78
215	65	303	154	102	45	4	3	2404	2722	54
307	84	318	184	100	34	4	3	2936	2340	47
399	117	300	146	111	40	4	3	3301	1963	39
491	85	336	172	101	62	4	2	3312	2739	55
584	81	339	196	105	34	4	2	3663	2499	50
676	62	306	148	109	45	4	2	2978	2774	55
803	249	341	148	150	33	2	2	1738	2649	53
987	66	335	189	116	27	2	2	2657	1702	34
1172	84	305	156	122	25	2	2	2134	1929	39
1310	65	161	77	56	27	2	2	2499	870	26
1638	45	310	166	113	27	2	2	3189	1312	394
1900	56	324	166	132	24	2	2	1563	2798	84
2162	48	300	140	122	31	2	2	2091	1937	194
2256	112	313	165	114	29	2	1	4659	1814	181
2517	38	340	152	143	39	4	3	4288	1713	171
2684	138	384	169	184	26	2	2	1555	3334	267
3045	70	214	79	115	19	2	2	1377	2098	168
3105	97	340	158	149	26	4	2	3574	2569	205
3231	64	332	166	135	29	2	2	2142	2092	84
3402	147	375	186	149	37	4	2	4042	2505	100
3475	143	436	204	179	41	4	2	5620	2095	84
3596	112	347	148	166	28	2	2	1471	3185	127
3718	181	380	140	198	37	4	2	2940	3490	140
3791	101	281	146	110	11	4	2	3887	1952	78
3840	174	305	161	112	30	4	2	2457	3352	134
3888	99	325	142	157	23	4	2	4976	1763	71
3961	269	333	123	171	33	2	1	4042	2224	89
4010	82	328	167	132	28	4	2	3509	2524	101
4083	392	503	211	244	37	4	3	1970	4596	184
4156	111	327	161	148	14	2	1	2685	3288	132
4205	244	789	366	366	45	4	3	5166	2749	110
4302	165	458	209	217	27	4	2	2887	4283	171
4448	45	339	166	139	30	4	3	3266	2242	90
4570	76	412	223	157	24	2	1	2383	4668	187
4692	67	300	121	141	33	2	1	1949	4156	166
4962	82	322	171	116	34	4	2	5581	1558	140
4994	87	314	147	129	36	2	1	3028	2800	252
5154	156	343	110	209	18	2	2	891	5197	468
5261	118	345	161	148	35	2	1	3903	2387	215
5475	34	331	162	154	13	2	2	2774	1611	145
5582	104	405	163	213	20	2	2	1580	3460	311
5676	62	381	144	222	12	2	2	1837	2800	1624
5697	244	640	252	352	26	4	3	4479	2572	1492
5719	246	412	117	271	12	2	2	1116	4984	2891
5751	73	300	129	135	34	4	3	4267	1519	5528
5836	192	346	111	205	22	2	2	1448	3226	129
6060	92	370	145	197	25	4	2	5176	1930	77
6396	97	328	117	190	17	2	2	1234	3588	144
6732	98	377	157	183	33	4	2	7574	1344	54
6956	116	345	145	176	19	2	2	1311	3553	142
7096	219	349	98	224	19	2	2	705	6683	2673

Appendix 6: Lead-210 dates. Source B – from this study.

Depth (cm)	Age (yr)	Standard Deviation (yr)
0	5	0
1	20	1
2	30	1
3	42	2
4	57	3
5	79	8
6	111	21
7	139	32
8	180	113

Appendix 7: Radiocarbon ages from Beta Analytic Inc. Source: (A) – LeBlanc (2002); (B) – this study.

Source	Depth (cm)	Conventional Radiocarbon yr BP	Lab. No.	Calibrated Calendar yr BP 1 Sigma	Calibrated Calendar yr BP 2 Sigma
A	30-35	1290 +/- 40	Beta-156532	(1180-1209) (1229-1280) 1180 – 1280	(1093-1106) (1137-1162) (1167-1297) 1093-1297
B	59-61	2120 +/- 40	Beta-204646	(2009– 2018) (2040 - 2148) 2009 - 2148	(1991 - 2160) (2169– 2178) (2244– 2301) 1991-2301
A	95-100	2410 +/- 40	Beta-156533	(2353-2487) (2645-2649) 2353 – 2649	(2345-2542) (2591-2615) (2636-2699) 2345-2699
B	153-154	3030 +/- 40	Beta-204647	(3167– 3181) (3207– 3272) (3284– 3330) 3167 - 3330	(3081–3092) (3110–3126) (3140–3356) 3081-3356
A	220-225	4290 +/- 40	Beta-156534	(4828-4876) (4945-4946) 4828 – 4946	(4729-4736) (4741-4750) (4820-4971) 4729-4971
A	295-300	4890 +/- 40	Beta-156535	5594-5647	5584-5717
B	349-350	4990 +/- 40	Beta-210910	(5652–5746)	(5606-5758) 5822-5885) 5606-5885
B	395-369	5000 +/- 40	Beta-204648	(5658-5749) (5829– 5854) 5658 – 5854	(5624–5625) (5644-5774) (5779–5796) (5803-5892) 5624-5892
B	453-456	6160 +/-40	Beta-204649	(7003-7030) (7040- 7072) (7076– 7088) (7093-7156) 7003-7156	6948-7165
A	544-549	6320 +/- 40	Beta-156536	(7174-7220) (7237-7278) (7283-7287) 7174 – 7287	(7163-7324) (7402-7409) 7163-7409

Appendix 8: Coordinates of modern pollen relating to fossil pollen used in the PCA.

Site number	Longitude	Latitude
22	-68.4830	63.7330
23	-68.4830	63.7330
25	-96.0000	64.3000
32	-83.2500	68.5330
45	-63.3670	58.6670
47	-101.0600	66.0800
51	-83.3700	64.2000
59	-95.4833	73.5167
63	-95.0000	69.9000
132	-43.5167	61.1667
150	-43.0933	60.0900
151	-43.0983	60.0933
184	-85.9935	72.2935
186	-81.1335	72.0502
204	-69.1608	66.1827
215	-65.5211	63.6031
216	-76.8593	63.5918
219	-70.7908	63.1850
220	-67.0683	62.6407
221	-68.2358	62.5133
224	-63.4587	65.4407
228	-65.7660	66.2670
230	-64.5860	65.8650
234	-85.6700	72.9110
239	-69.9350	65.6920
242	-68.1750	65.9170
244	-67.2950	66.0990
250	-76.1550	64.6800
253	-78.0190	64.5790
257	-75.7250	64.4760