Pollen based inferences of post-glacial vegetation and paleoclimate change on Melville Peninsula, Nunavut, Canada

by

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A thesis submitted in conformity with the requirements for the degree of Master of Science
Graduate Department of Geography
University of Toronto

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Abstract

Pollen analysis of a sediment core from Lake SP02, Melville Peninsula, Nunavut, Canada provides a ~6300 year record of post-glacial vegetation and climate change. Dominant local and regional taxa identified include Cyperaceae, Ericaceae, Artemisia, Salix, and Oxyria. Fossil pollen assemblages, pollen accumulations rates, and variations in sediment organic matter, indicate a period of optimal Holocene warmth between 5300-3900 yr BP, followed by a prolonged period of Neoglacial cooling, as well as a period of relative warmth between 1300-1000 yr BP, interpreted as evidence for the Medieval Warm Period. Variations in pollen abundances and accumulations during the 20th century suggest a response to recent warming that is unprecedented since deglaciation of the Peninsula. Comparisons of the timing and rates of multi-scale climate variations for Melville Peninsula with adjacent sites reveal a potential late Holocene shift in the boundary separating continental and maritime climate regions in the eastern Canadian Arctic.
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1 INTRODUCTION

The Earth’s climate is rapidly changing, and there is strong evidence to suggest that this change is amplified in Arctic regions due to several positive feedbacks (Serreze et al. 2003). Such feedbacks include decreased surface albedo associated with ice and snow melting, trapping of heat near the surface due to atmospheric stability, and the effect of cloud dynamics on insolation (Curry et al. 1996). In addition, the Arctic also influences climates at lower latitudes through changes in river runoff, effects on the global thermohaline circulation, impacts on atmospheric circulation, and modulation of atmospheric CO₂ and CH₄ concentrations (Overpeck et al. 1997). However, predictions of the rate and magnitude of future global climate change, as well as the resulting impacts on the biosphere, are made difficult by the complexity of climatological and ecological systems. Therefore, studies that aim to document past climate variability and the associated effects on Arctic ecosystems are considered essential to better understanding the causes and potential impacts of climate change.

Most instrumental climate records from the Canadian Arctic extend only as far back as the 1950’s. Therefore, the nature of climate variability in the past must be inferred from the analysis of environmental proxies preserved in sediment, peat, and ice deposits. Some of the most commonly used biological and non-biological indicators used to make paleoclimate inferences include microfossil assemblages, and geochemical analysis of lake sediments and peat deposits, including loss on ignition (LOI) (Dean 1974), and magnetic susceptibility (MS) (Thompson et al. 1975), as well as glacier ice cores which contain high-resolution records of
variations in delta $^{18}$O and summer melt percentages from as far back as the last glacial period (Fisher et al. 1995). Of these proxies, the analysis of fossil pollen preserved in depositional sequences remains one of most well established sources of paleoenvironmental information (Bennett and Willis 2001).

The purpose of this study is to provide a well dated and high-resolution paleoenvironmental record for Melville Peninsula, Nunavut, Canada by producing the first pollen diagram from this area (Figure 1). The pollen stratigraphies, as well other proxies, are based on analysis of a sediment core collected from a small Arctic lake unofficially named SP02 (Figure 2). The primary objectives of this study are to document the response of local and regional terrestrial vegetation to post-glacial environmental variability, as well as to investigate the nature of middle to late Holocene paleoclimate change with respect to the study site.

1.1 Pollen analysis

Pollen are ideal indicators of past climate conditions because the relationships between the plants that produce pollen, and the environmental conditions required for optimal growth of these plants have been well established (Traverse 1988; Bennett and Willis 2001). In addition, Arctic vegetation has been shown to respond rapidly and synchronously to abrupt climate changes during the Holocene (Gajewski and Atkinson 2003). Therefore, fossil pollen preserved in depositional sequences, such as lake sediments, can be analyzed to reconstruct terrestrial plant assemblages of the past, which can then be interpreted to infer paleoclimatic variability at multiple spatial and temporal scales (Gajewski 2002; Viau et al. 2006).
Palynomorphs, including pollen produced by angiosperms and gymnosperms, as well as spores produced by other vascular plants and mosses, are dispersed mainly by wind, but also by alternate vectors such as water, insects, and other animals. Only a small fraction of the total annual production of pollen by a plant is utilized in fertilization. The remainder of this pollen production is atmospherically deposited on land or sea surfaces as ‘pollen rain’, where it may later become incorporated and preserved in the sediments of lakes and ponds.

One of the most significant characteristics of pollen as paleoenvironmental indicators is the fact that the outer exine of each pollen grain is comprised of sporopollenin, which is a substance highly resistant to most chemical and physical degradation (Bennett and Willis 2001). Therefore, pollen can be preserved indefinitely in anaerobic environments such as most lake sediments. Once isolated from extraneous sedimentary material, pollen can be taxonomically identified on the microscope to at least the Family level, but sometimes to the species, by analyzing the size and shape of the pollen grain, in addition to the type and degree of surface sculpturing of the outer wall. These observations are then compared to pollen contained in reference collections, as well as images and descriptions found in the literature.

Since the optimal environmental conditions for the growth of many Arctic plants has been well documented, studies of pollen preserved in sedimentary sequences can be used to both reconstruct past terrestrial vegetation assemblages, and to indirectly infer past environmental conditions such as temperature and precipitation (Gajewski 2002; Zabenskie and Gajewski 2007). In addition, pollen diagrams produced from well-dated sediment sequences can be utilized to investigate the timing and rates of paleoenvironmental changes at multiple time scales. However, the dynamics of the relationships between fossil pollen assemblages, the plants that
produced them, and the associated climatic conditions are complex, resulting in a series of assumptions with respect to pollen-based paleoenvironmental reconstructions.

Pollen analysis is limited by a series of factors, which can be particularly problematic in Arctic settings. Such issues include pollen transported over long distances, low pollen concentrations, contamination by fossil pollen from older deposits, and unreliable chronological control (Gajewski et al. 1995). A fraction of the pollen deposited at a given site is referred to as ‘local’ pollen, and originates from the immediate area. However, a significant portion of the pollen comes from a larger area, and is referred to as the ‘regional’ component. A third source is pollen that is deposited over very long distances (Birks and Birks 1989). Long distance transport of pollen can be particularly problematic in samples from Arctic sites, where the high concentration of pollen from forests at lower latitudes can dilute and obscure the relatively low concentration of local and regional pollen. Therefore, it is important to establish the source of the pollen identified in the record when interpreting temporal variations in the relative abundances of taxa represented in a pollen diagram. It is also important to note that the long-distance component of an Arctic pollen diagram can be useful for inferring potential changes in the strength and trajectory of past air masses and atmospheric currents (Bourgeois et al. 2000; Barry et al. 1981).

The relatively low concentration of pollen typically associated with Arctic lake sediments is also problematic. Pollen concentrations in Arctic settings can be as low as 1000 grains/cm³ due to the relatively low density of vegetation on the landscape; whereas typical concentrations in sediments of lakes in the temperate zone are orders of magnitude higher by comparison (Gajewski et al. 1995). As a result, slides prepared from Arctic sediment samples can have fewer than 20 grains per slide (Zabenskie and Gajewski 2007). Because typical pollen sums
range from 300 to 500 grains per level, and because each slide requires several hours on the
microscope, the low concentration of pollen in Arctic lake sediments often results in low
resolution pollen diagrams from a limited number of sites. To obtain an adequate pollen sum,
Arctic pollen studies typically require larger sediment samples and more time in the laboratory
identifying and counting pollen (Gajewski et al. 1995).

Another potential problem in Arctic pollen studies is contamination of the fossil pollen
assemblage by older deposits within a sequence. Several areas of the Canadian Arctic are
underlain by Tertiary sediments which can contribute pollen to Holocene deposits through
erosion and surface runoff (Hodgson 1985). Fortunately, palynomorphs associated with the
Tertiary sequences are often sufficiently different from most late Quaternary pollen types to
allow for relatively easy identification of contaminated samples (Gajewski et al. 1995).

A final, yet equally important, issue facing pollen studies in Arctic settings is the
difficulty typically associated with the establishment of a reliable chronology for the sediment
sequence (Gajewski et al. 1995; 2000). Organic material is required for radiocarbon dating, but
such material is often lacking in Arctic lake sediments due to the low biological productivity of
the associated landscape. Therefore, an inordinate amount of time is required to collect an
adequate sample of organic material for dating. In many cases, the concentration of organics is
so low, that bulk sediment samples must be utilized, which ultimately introduce additional
sources of error and uncertainty with respect to chronological estimates (Zabenskie and Gajewski
2007).

As a result of the difficulties associated with pollen analysis, special care must be taken
when selecting a lake or pond to sample. One should select a body of water that exceeds 3 m in
depth to ensure that the entire water column does not freeze during winter months. The sediment accumulation rate should also be sufficient to allow reasonable temporal resolution of the resulting pollen diagram, as too low a rate will result in insufficient volumes of sediment for a meaningful analysis. The topography of the surrounding area must also be considered as substantial relief can influence local climate and associated ecology. Finally, the geology of the study site must be taken into account, as the composition of associated parent material will have an effect on nutrient levels and plant production. For example, some areas of the high Arctic are underlain by Tertiary deposits that include the spores of ancient plants, while much of the middle Arctic is associated with nutrient-poor carbonates, with low arctic sites typically underlain by granitic rocks of the Canadian Shield (Bone 2003).

The vegetation of the Canadian Arctic can also be characterized in terms of high, middle, and low arctic regions. The types and abundances of different plant taxa vary among these regions, which is reflected in the respective modern pollen assemblages (Gajewski 2002). These differences are the result of variations in climate, topography, and geology of the associated regions. For example, the low Arctic exhibits relatively higher density of plant cover, and height of woody and vascular plants such as Salix and Betula, when compared to regions designated as high Arctic (Bliss 1988). The least diverse region of the Canadian Arctic is found in the extreme northwest, due to a more homogenous topography, and a colder and drier climate (Porsild 1964). The more mountainous topography of the eastern Arctic, on the other hand, results in more diverse habitats, and sometimes in increased biological productivity (Gajewski et al. 1995).

The most important variables constraining plant growth at high-latitudes are mean July temperature and mean annual precipitation (Billings 1987). Both of these variables have been shown to be the most important factors influencing the amount of snow and ice cover that
persists on the landscape during the short summer growing season. Variations in these environmental parameters can result in changes in plant density, above-ground biomass, the number and size of flowers, and the quantity of pollen produced by each plant; such effects however vary by species (Chapin and Shaver 1985; Delph et al. 1997; Peros and Gajewski 2008). For example, under relatively warmer conditions, *Papaver radicatum* increases in above-ground biomass and number of flowers produced (Molgaard and Christensen 1997), while *Dryas octopetala* produces taller and larger flowers (Welker et al. 1997).

Many of the genera typical of the Canadian Arctic are capable of growing in a wide range of ecological conditions, and are distributed throughout the Arctic regions of both Europe and North America (Porsild 1964). Therefore, the type of vegetation found on the landscape may change very little through time, while the density and productivity of the vegetation can vary in accordance with fluctuations in climate. This can make variations in pollen concentrations and accumulation rates more sensitive environmental indicators when compared to changes in pollen percentages alone. For example, at Lake KRO2 on Victoria Island, Peros and Gajewski (2008) reported relatively stable pollen percentages for the past 10 ky, while fluctuations in local and regional pollen influx (<10 to 500 grains/cm²/year) provided strong evidence for a response to changing environmental conditions, likely due to changes in plant structure, density, and productivity (Peros and Gajewski 2008).
1.2 Studies of fossil pollen from the Canadian Arctic

A number of pollen records have been produced from various sites in the Canadian Arctic Archipelago, including studies from Ellesmere Island (Hyvarinen 1985), Banks Island (Gajewski et al. 2000), Prince of Wales Island (Gajewski and Frappier 2001), Victoria Island (Peros and Gajewski 2008), and Somerset Island (Gajewski 1995), as well as pollen diagrams from Boothia Peninsula (Zabenskie and Gajewski 2007), and Baffin Island (Andrews et al. 1979; Short et al. 1989; Wolfe et al. 2000). Several pollen records have also been obtained from the coastal regions of Greenland (Bay and Fredskild 1997; Wagner et al. 2000; Bourgeois et al. 2000). In addition, there are recent sources of modern pollen samples for use in calibration, which are available for a number of the high, central, and eastern Arctic islands (Gajewski 2002; Kerwin et al. 2004). A review of these pollen studies is important for identifying and understanding some of the key advantages and limitations of pollen analysis from sites in the Canadian Arctic.

A core from Rock Basin Lake on Ellesmere Island was analyzed for pollen by Hyvarinen (1985). The pollen diagram was divided into 4 zones, the first of which corresponded to 9000 to 8000 yr BP, and was dominated by pollen from Cyperaceae and Poaceae. *Oxyria* also increased in abundance during this period, with low percentages of Arctic herb pollen such as Ranunculaceae, Caryophyllaceae, *Papaver*, and *Potentilla*. This was interpreted as pioneer vegetation immediately following deglaciation of the area, which later saw a shift with the introduction of Ericaceae, and *Salix* (Hyvarinen 1985).

The second zone covered the period from 8000 to 7000 yr BP, where low concentrations of Ericaceae were reported, along with an increase in *Salix* as high as 60%. The appearance of Ericaceae is interpreted as possible evidence for shrinking snowbeds in the area, which would be
conducive to the persistence of low-lying herbaceous ground cover (Hyvarinen 1985). The third zone, from 7000 to 3500 yr BP showed an increase in Ericaceae, and simultaneous decreases in *Salix* and *Oxyria*. The forth zone covers the period 3500 yr BP to present and showed increases in the abundances of Ranunculaceae, Caryophyllaceae, *Dryas, Papaver,* and *S. oppositifolia*. This was interpreted as evidence for a shift towards cooler temperatures, which impacted the local vegetation assemblage after a prolonged period of vegetational stability (Hyvarinen 1985). Also of importance are variations in pollen concentrations which decrease from 1500-2000 grains/cm³ in the two oldest zones, to only 100-200 grains/cm³ in the uppermost zone, which is generally consistent with a pattern of Neoglacial cooling, and decreased biological productivity.

This pattern of peak warmth in the early Holocene, followed by a prolonged period of Neoglacial cooling has been reported from Arctic islands at lower latitudes (E.g. Gajewski et al. 2000; Gajewski and Frappier 2001). However, the study by Hyvarinen (1985) produced only qualitative inferences of paleoenvironmental conditions based on pollen percentages and concentrations, and failed to achieve a temporal resolution sufficient for investigations of Holocene climate variations at sub-millennial time scales.

Four sediment cores were obtained for pollen analysis from Banks Island, Northwest Territories (Gajewski 2000), including Muskox Lake, 74MS12, and 74MS15 from a middle Arctic vegetation zone, and 74MS11 from a high Arctic vegetation zone. Difficulties with radiocarbon dating of these cores due to contamination of organic material from older levels prevented accurate age estimates. However, it was possible to correct some of these issues based on cross-correlations of the pollen stratigraphies (Gajewski 2000). Each pollen diagram was divided into three separate zones, corresponding to the early, middle, and late Holocene respectively.
In zone 1, the early Holocene, all of the Banks Island records show dominance of Poaceae, and relatively low values of Cyperaceae, Betula, and Salix. The only exception to this is the high Arctic site, where pollen representing Poaceae was lower in abundance compared to those from Cyperaceae (Gajewski 2000). In zone 2, percentages of Cyperaceae and Betula decreased at all of the sites, with the exception of the high Arctic site. Picea, Pinus, and Alnus abundances increased at Muskox Lake and the high Arctic site, while only Picea shows an increase at this time from 74MS12 in the middle Arctic. In zone 3, which covers the last few thousand years, all sites show increases in the amount of Poaceae pollen, with simultaneous decreases in Cyperaceae in all sites except Muskox Lake. Differentiating this zone from zone 1 is the fact that in the late Holocene, pollen percentages of Arctic taxa such as Dryas and Oxyria increased, while long-distance pollen representing Betula remained low (Gajewski 2000). The third zone is also characterized by relative increases in the abundance of Artemisia in most of the records.

Taken together, the four cores from Banks Island, show post glacial conditions and the inception of modern lakes at approximately 9000 yr BP (Gajewski 2000). During the early Holocene there is evidence for middle Arctic vegetation for the sites occupying the southern portion of the island, with high Arctic vegetation represented at the more northern site. A period of optimal environmental conditions for the associated taxa was observed during the mid-Holocene, followed by a prolonged period of climatic cooling (Gajewski 2000).

A similar pattern of millennial-scale Holocene climate change has been reported from Arctic sites both to the north (Hyvarinen 1985), and to the south (Zabenskie and Gajewski 2007) of Banks Island. However, analysis of the spatial variability of Holocene environmental change through comparisons of the timing of major climate events is difficult due to uncertainties in the
associated chronologies. Also, similar to most pollen studies from the Canadian Arctic (E.g. Hyvarinen 1985), the pollen diagrams produced from Banks Island (Gajewski 2000) were used only for qualitative inferences of past climate conditions, and did not achieve a temporal resolution sufficient for investigations of climate change at the sub-millennial scale.

Analysis of a sediment core from Prince of Wales Island (Gajewski and Frappier 2001) found very low pollen concentrations, low levels of organic matter, and high carbonate content in the basal portion of the core dated to older than 6500 yr BP. The estimates of organic matter and carbonate content in this study were based on the loss on ignition (LOI) (Dean 1974). Around 6500 yr BP, pollen concentrations began to increase, mainly due to increases in the abundances of Cyperaceae and Dryas. Prior to this period, pollen abundances of Poaceae and Papaver were higher, indicating that temperatures were likely cooler for the earliest portion of the record. Pollen concentrations, including Cyperaceae, decreased after 4000 yr BP, suggesting a shift again toward cooler temperatures, consistent with a period of Neoglacial cooling reported from other sites (Kerwin et al. 2004). Also supporting this interpretation are the results of modern pollen data from surface samples which show a general decrease in pollen concentrations with increased latitude and cooler temperatures (Gajewski 1995). During this same period, the relative abundances of Poaceae, Brassicaceae, Ranunculaceae, and Saxifraga oppositifolia increase (Gajewski and Frappier 2001). This is also consistent with cooling climate conditions as these taxa are more typical of high Arctic sites (Gajewski 1995). Long-distance transport of Betula decreased throughout the majority of the record, while pollen representing low arctic tundra, and forests to the south remained relatively constant (Gajewski and Frappier 2001).

Pollen analysis was conducted on lake cores from two separate lakes on Somerset Island (Gajewski 1995) to investigate variations in Holocene climate for the region. One site, named
RS29 is located in the high Arctic vegetation zone, while the other site, named RS36, is in the middle Arctic zone. Both cores are similar in that they show very low levels of organic matter, and little variation in carbonate content, based on LOI. Both records also show a general decrease in pollen concentrations since 6000 yr BP, with the middle Arctic site showing pollen concentrations that were approximately three times greater prior to 6000 yr BP compared to those reported at later time periods (Gajewski 1995). For both sites, pollen concentration and accumulation rates were highest during the period 5000 to 6000 yrs BP, and neither showed significant changes during the last 1000 yrs.

The pollen assemblage from the high Arctic site, RS29, was dominated (>50%) by long-distance pollen of *Betula, Pinus, Picea,* and *Alnus crispa* from the forests to the south. Local and regional taxa indentified include Cyperaceae, Poaceae, Ericaceae, *Salix, Cassiope,* and *Oxyria digyna.* The pollen diagram from the middle Arctic site, RS36, showed generally less than 40% long-distance pollen, with increased abundances of Cyperaceae, Rosaceae, and *S. oppositifolia,* and decreased Ericaceae, compared to the high Arctic site (Gajewski 1995). The core from RS29 also shows peak abundance of *Salix* during the earliest period in the record, while Cyperaceae and *Oxyria* exhibit simultaneous decreases in abundance.

The pollen records from Somerset Island (Gajewski 1995), when taken together, suggest a pattern of Holocene climate change that is congruent with records from most other sites in the Canadian Arctic (E.g. Hyvarinen 1985; Gajewski 2000; Gajewski and Frappier 2001), where mean summer temperatures were warmest in the mid-Holocene, and gradually decreased throughout the remainder of the record. While the composition of the associated vegetation for the Somerset Island sample sites appeared to change very little throughout the Holocene, changes in the density of the vegetation on the landscape, as inferred from variations in pollen
concentration and accumulation rates, also provide evidence for peak Holocene warmth followed by a prolonged period of Neoglacial cooling (Gajewski 1995). The inclusion of estimates of pollen accumulation rates in this study represents an improvement over previous pollen analysis, which reported only pollen concentrations (E.g. Hyvarinen 1985). Also referred to as ‘pollen influx’, the pollen accumulation rate takes into account variations in the sediment accumulation rate of the lake, which could otherwise result in fluctuations in the pollen concentration during a period where the influx of pollen to the sediments remained constant through time. However, accurate calculations of pollen accumulation rates are dependent on reliable dating of the sediment core, which is not necessarily available for many lake sediment records from the Canadian Arctic (E.g. Gajewski 2000).

A study from Baffin Island (Andrews et al. 1979) produced a pollen diagram from a 1.2 m sediment core from Windy Lake, Pangnirtung Pass. The chronology for the core was established using radiocarbon dating, with the basal sediments corresponding to approximately 3000 yr BP. From the oldest section of the record up until about 2500 yr BP, Poaceae, Caryophyllaceae, Salix, and Alnus, all show increases in relative abundances. Following this period, and up until 1500 yr BP, pollen concentrations and accumulation rates show a gradual decrease, with more rapid decreases reported for the period 1500 to 1000 yr BP. This was interpreted as evidence for more optimal environmental conditions earlier in the Holocene, followed by a prolonged period of progressively cooler temperatures. Conditions appear to have improved around 800 yr BP, as suggested by increases in the abundances of Cyperaceae, Caryophyllaceae, Salix, Alnus, and Betula. Pollen concentrations then decreased following this period up until about 650 yr BP at which point the record terminates.
One of the most important contributions of the study from Baffin Island (Andrews et al. 1979) is the sub-millennial to centennial scale temporal resolution of the pollen record. This improvement over most of the other studies previously reviewed permits investigations of climate change at multiple temporal scales. For example, the apparent cooling in environmental conditions at the end of the record may indicate a sub-millennial scale climate event referred to as the Little Ice Age (LIA), which has been reported from other Arctic sites (Overpeck et al. 1997; Finkelstein and Gajewski 2007).

The first quantitative reconstruction of Holocene climate from the western Arctic was based on pollen analysis of a lake sediment core (KR02) from Victoria Island (Peros and Gajewski 2008). The basal sections of the core were radiocarbon dated to approximately 10,000 yr BP, where magnetic susceptibility values were relatively high, organic matter concentrations were less than 10%, and long-distance Betula pollen dominated the pollen diagram. The pollen percentage data indicate an increase in Arctic herbs, including Artemisia, Oxyria, Dryas, and S. oppositifolia, in response to long term Neoglacial cooling (Peros and Gajewski 2008). Further support for the impact of regional and global climate change on Arctic plant communities is the fact that variations in the influx rates of local and regional pollen from KR02 track several major changes observed in the GISP2 ice-core record (Alley 2004). The uppermost sediments of KR02 show significant increases in organic matter, local and regional pollen accumulation rates, and abundance of Cyperaceae, while the abundances of Arctic herbs, such as Artemisia, Oxyria, and Papaver, show synchronous decreases. This was interpreted as the impact of recent warming due to anthropogenic emissions of greenhouse gases over the past 150 years.

Modern analogue and transfer function techniques were used to generate quantitative reconstructions of mean July temperature and total annual precipitation, in an attempt to provide
historical context for recently observed climate changes (Peros and Gajewski 2008). Results indicate that July temperature cooled by 1-1.5°C over the course of the Holocene, with an increase of approximately 0.5°C during the past 100 years. Peak Holocene warmth was realized at approximately 9000 yr BP, with temperature values very similar to those estimated by Kaufman et al. (2004). However, these conditions terminated much earlier when compared to estimates from Banks and Prince of Wales Islands (Gajewski et al. 2000; Gajewski and Frappier 2001). Such comparisons were made possible in this case by the fact that reliable calibrated radiocarbon ages were provided for the KR02 record.

Quantitative reconstructions of Holocene temperature were also produced from pollen analysis of a sediment core from Lake JR01, Boothia Peninsula, Nunavut (Zabenskie and Gajewski 2007). The entire record spans 7200 years, based on 10 radiocarbon dates, and major taxa observed include Cyperaceae (>50%) and Salix, with long-distance Pinus pollen comprising more than 30% in the earliest sections of the core. An increase in the abundances and concentrations of taxa typical of the mid-Arctic suggest that warmer conditions existed during the middle Holocene, with decreasing pollen concentrations following this period consistent with Neoglacial cooling, and increases in Salix, and Cyperaceae in the past 35 years as a result of recent global warming (Zabenskie and Gajewski 2007).

Reconstructions of July temperature from JR01 using the modern analogue technique suggest that the mid-Holocene (5800 to 2800 yr BP) was approximately 1°C warmer compared to the last 1000 years (Zabenskie and Gajewski 2007). Quantitative reconstructions of mean July temperature during the early to middle Holocene from the western Canadian Arctic (Peros and Gajewski 2008) suggest that the onset of peak temperatures occurred several thousand years earlier when compared sites in the eastern Arctic. The pollen study from JR01 on Boothia
Peninsula (Zabenskie and Gajewski 2007) is also important because it was the first study of post-glacial lake sediments in the Canadian Arctic to employ and describe a heavy liquid separation technique to isolate and concentrate pollen from the sediment matrix, which I have adopted and outlined in the methodology section of this report.

Pollen can also be extracted and analyzed from ice cores, in addition to lake sediments. One of the benefits of an ice core record is that they are often annually resolved, facilitating investigations of environmental changes at multiple temporal scales, including centennial, decadal, and annual. An ice core from the Agassiz Ice Cap, Ellesmere Island was obtained and analyzed for pollen by Bourgeois et al. (2000). Because there is no local vegetation on the Agassiz Ice Cap, the resulting pollen diagram was comprised entirely of long-distance pollen, and was used to reconstruct variations in past atmospheric circulation. In addition, variations in the abundances of non-arboreal taxa were also used to interpret changing conditions associated with the regional tundra (Bourgeois et al. 2000).

Two separate zones were identified in the ice core record, the first of which corresponds to the period 11,500 to 6000 yr BP. During this period, concentrations of pollen from southern tress, as well as Poaceae, Ericaceae, and Cyperaceae, all show maximum values prior to 7000 yr BP (Bourgeois et al. 2000). *Picea* and *Pinus* reached maximum abundances, while *Alnus* was sparse or absent, and *Betula* fluctuated between 5 and 25%. Zone II represents the period 6000 yr BP to present, and is characterized by a decrease in the abundances of pollen from southern Boreal taxa. For example, the abundance of *Picea* pollen decreases from over 20% in zone I, to less than 10% in zone II. During this same period, *Salix* and *Oxyria* increase in relative abundance, while most other tundra pollen were absent (Bourgeois et al. 2000). For the past 1000 years, *Pinus* was the most dominant taxon with an increase from 14% to 74% between
1600 AD and 1900 AD. The most dominant herbaceous taxa were Poaceae at 16%, and *Oxyria* at 8%. With the exception of *Oxyria*, all of the pollen taxa, including *Pinus, Picea, Betula, Alnus, Poaceae, Cyperaceae, Ericaceae, and Salix*, show increased concentrations between 1000 AD and 1200 AD, and remained constant until about 1600 AD. Following this period, pollen concentrations increased again, with the exception of *Pinus*, and peaked between 1800 AD and 1850 AD.

The periods of relatively higher non-arboreal pollen concentrations prior to 6000 yr BP can be interpreted as an increase in the density of terrestrial vegetation, and potentially a warmer climate, if one assumes that all herbaceous pollen are of regional origin. Supporting this interpretation is a study from the northwestern mainland of Canada (Ritchie et al. 1983), where similar pollen types show synchronous variations in concentration during this same time period. In addition to millennial scale climate variations in the early Holocene, the ice core record also shows centennial and decadal scale variations during the past 1000 years, which generally correspond to climate events such as the LIA reported from other Arctic sites (Overpeck et al. 1997). Earlier in the Holocene concentrations of *Picea* pollen in the Agassiz record were high, while the treeline to the south was simultaneously retreating south as forested zones were being converted to tundra. The relative increases in long-distance arboreal pollen during this time were therefore interpreted as the result of a potential increase in wind frequency from the southwest during spring and early summer (Bourgeois et al. 2000).

In summary, a review of pollen studies from several regions of the Canadian Arctic and Greenland, including both lake sediments and ice cores, reveal broadly similar patterns of climate change for the Holocene at multiple time scales. Most pollen records show conditions for the mid-Holocene that were relatively warmer when compared to present day conditions, as
indicated by increased pollen concentrations and abundances of low to mid-Arctic taxa such as Salix and Cyperaceae. Following a period of mid-Holocene warmth, often referred to as the Holocene Thermal Maximum (HTM), all records show a prolonged period of progressively cooler temperatures termed Neoglacial cooling, as suggested by decreased pollen concentrations, and relative increases in the percentages of high Arctic taxa such as Dryas and Poaceae. However, a review of pollen studies from the Canadian Arctic also highlights some of the inherent problems and limitations when using pollen as a proxy for paleoenvironmental inferences. The most important deficiencies that have been identified include a low density of study sites, low temporal resolution of the existing pollen diagrams, problems with radiocarbon dating of sediment cores, and a lack of quantitative estimates of past climates (Gajewski et al. 1995; Kaufman et al. 2004; Zabenskie and Gajewski 2007).

The low density of pollen studies from the Canadian Arctic, combined with dating problems, makes comparisons of the spatiotemporal variability of Holocene paleoclimates exceedingly difficult. In addition, the low temporal resolution of the majority of the existing pollen diagrams from the region does not facilitate investigations of vegetation and climate changes at sub-millennial time scales. With the exception of pollen studies from ice cores, most pollen diagrams have not shown evidence for higher-frequency and short-term climate fluctuations such as the LIA. Therefore, while several pollen studies have provided descriptive estimates of the paleoenvironments of the Canadian Arctic during the Holocene, there remain many unanswered questions regarding the postglacial climates and the associated impacts on terrestrial vegetation (Gajewski and Atkinson 2003; Zabenskie and Gajewski 2007). For this study, I have attempted to provide new information on Holocene vegetation history and climate variability for the study site.
1.3 Arctic paleoclimates

The preceding review of palynological studies from the Arctic shows that climate is a fundamental driver of vegetation change. This section reviews the general patterns, as well as the potential mechanisms of Holocene climate change. Proxy-based reconstructions of Arctic paleoclimate suggest that climate changes in the Canadian Arctic were ubiquitous throughout the Holocene, and occurred at multiple spatiotemporal scales (Kaufman et al. 2004).

**Millennial-scale Climate Variability**

Orbitally-driven variations in insolation are generally accepted as the primary driver of millennial-scale climate changes during the Quaternary period (Hays et al. 1976; Imbrie et al., 1984; Duplessy et al., 2008). However, there are a number of complex and nonlinear internal feedbacks within the Earth’s cryospheric-hydrospheric-atmospheric system that are capable of amplifying or moderating the climate response to the initial orbital signal.

More specifically, there are three main orbital parameters collectively referred to as Milankovitch cycles that influence the seasonal intensity of solar radiation, and are thought to be the main causes of large-scale climate shifts (Duplessy et al. 2008). Obliquity refers to variations in the tilt of the Earth’s axis on time scales of ~41 ka, which affects the amplitude of seasonal climate variations in both hemispheres. In addition, precession of the equinoxes on time scales of ~21 ka determines the time of perihelion when the Earth is closest to the sun. Finally, eccentricity of the Earth’s orbit around the sun on time periods of ~100 to 400 ka affects both the seasonal and total annual insolation of the Earth.
Both marine sediment cores and ice cores contain records of climate variations that provide evidence in support of the astronomical theory of climatic change (Bassinot et al., 1994; EPICA, 2004). However, it is also important to acknowledge that internal feedbacks between various Earth system components play an essential role in the amplification of initial external forcing. For example, major non-linear interactions of ice volume instability, isostasy, carbon cycling, and ocean-air-sea-ice system fluctuations can create positive feedbacks that amplify orbital forcing to produce glacial and interglacial cycles (Duplessy et al. 2008). In addition, these broad scale forcing mechanisms manifest at the local level by interacting with local-scale factors such as topography, soil development, and vegetation type (Chapin et al. 2000).

The Holocene Thermal Maximum (HTM) refers to an interval of warmth associated with peak Holocene temperature in the western Arctic, including Arctic Canada. Indicators of summer temperature suggest that the warmest interval of Holocene temperature in the Canadian Arctic began on average 8.8+/−2.1 ka BP and ended 5.9+/−2.6 ka BP (mean+/−standard deviation) (Kaufman et al. 2004). However, this warming occurred at various times and to different degrees in different places throughout Arctic Canada.

Much of the variability in the timing of the HTM is longitudinal in nature, where Canadian Beringia in the northwest warmed much earlier than northeastern Canada. For example, there strong spatial variability between the eastern and western regions of the continent in the response of atmospheric temperature to insolation forcing during the early Holocene (CAPE 2001). While uncertainties do exist regarding the reconstruction of the spatiotemporal pattern of the HTM owing to problems with chronological control, there remains a clearly observable pattern in the timing and duration of the HTM between the major regions of the Canadian Arctic (Kaufman et al. 2004).
Northwestern Canada spans from western Yukon to the northwestern portion of the Mackenzie District. Clear evidence for the HTM in northwestern Canada comes, for example, from the Tuktoyaktuk Peninsula, where analysis of *Picea* pollen and needles from lake sediments suggests that forests were approximately 75 km northward of their present-day limit between 12.2 ka BP and 5.6 ka BP (Kaufman et al. 2004). Northwestern Canada experienced the HTM by 10.6+/-1.5 ka, and transitioned to near-modern temperatures between 6.7 ka BP and 5.6 ka BP (Kaufman et al. 2004).

Two important physiographic features that strongly influenced Holocene climate in the northwestern region of the Canadian Arctic are the vast portions of ice-free areas during the last glacial period, and the presence of large and shallow continental shelves (Kaufman et al. 2004). As summer insolation increased towards the end of the last glacial period, the northwestern region absorbed solar energy by land rather than reflected by ice, contributing to relatively rapid warming (Kaufman et al. 2004).

The Canadian Arctic Islands span from the west coasts of Banks and the Queen Elizabeth islands on the Arctic Ocean, to the east coasts of Ellesmere and Baffin islands in the northeast North Atlantic Ocean (including the study site). This area was occupied by the Laurentide and Innuitian ice sheets until 11.5 ka BP to 9 ka BP in general, and until 8 ka BP to 6 ka BP in the Foxe Basin-Baffin Island region and Ellesmere Island (Dyke and Morris 1990). Ice cores and macrofossil indicators suggest that the Arctic Islands region experienced the HTM much later than in the northwest (Kaufman et al. 2004). For example, a diatom analysis from Melville Peninsula (Adams and Finkelstein 2010) places the timing of the HTM between 4400 and 2900 yr BP based on peak diatom concentrations and %BSi.
Cooling of the climate following maximum Holocene summer temperatures is referred to as ‘Neoglacial cooling’, which generally occurred in the same order as conditions warmed. The HTM ended first in the northwest about 9.1±/−2.0 ka BP, at 4.9±/−2.6 ka BP in the Arctic Islands, and finally at 4.3±/−2.2 ka BP in northern continental Canada. It is interesting to note that the standard deviations associated with the mean timing of terminations both within and between regions are about 20% higher than those associated with the timing of initiation (Kaufman et al. 2004), suggesting increased asymmetry in the onset of Neoglacial cooling in the Canadian Arctic.

The duration of the HTM in Arctic Canada appears to increase in an easterly and northerly direction, with the HTM lasting approximately 2200+/−1300 years in the northwest, 3100+/−1700 years in northern continental Canada, and 3400+/−1400 in the Canadian Arctic Islands (Kaufman et al. 2004). Furthermore, 16 terrestrial and 6 coastal sites have reported quantitative estimates of the magnitude of temperature increase during the HTM, where a variety of approaches have all yielded estimates within the range of 0.5-3°C, with an average of 1.6+/−0.8°C warmer than the mid-20th century mean. While the timing of the HTM varied spatially, the magnitude of temperature increase was generally equivalent throughout the Canadian Arctic (Kaufman et al. 2004).

Sub-Millennial and Centennial-scale Climate Variations

In addition to millennial-scale climate variations, such as the HTM, proxy indicators also suggest that sub-millennial to century-scale variability is superimposed on these longer-term changes (Overpeck et al. 1997). Neoglacial cooling due to decreasing summer insolation following the HTM, coupled with other changes in climate forcing led to successively cooler
summers in the late Holocene. This trend culminated in a period known as the Little Ice Age (LIA). The onset of the LIA in the Canadian Arctic is generally thought to have occurred during the early 17th century and ended during the mid 19th century (Overpeck et al. 1997).

Support for the LIA in Arctic Canada is found in several diatom-based records which document both biological and non-biological responses to changes in climate (Podritske and Gajewski 2007; Wolfe 2003). For example, a study of diatom community dynamics based on analyses of lake sediment cores from Prescott Island, Nunavut found decreases in species diversity corresponding to the onset of the LIA (Finkelstein and Gajewski 2007). Such changes are consistent with summer temperatures that are lower than the mid-20th century average. However, as with lower-frequency climate variations, there is regional and local variation in the timing and duration of the LIA across Arctic Canada. For example, many sites yield temperatures between 1700 AD and 1820 AD that were warmer than anything experienced later in the 19th century (Overpeck et al. 1997).

The main factors causing the LIA are different than those associated with lower-frequency climate changes such as the HTM. A lack of a distinct and prolonged cold period associated with the Maunder sunspot minimum period (1600 AD to early-1700 AD) suggests that solar forcing played a less dominant role over the past 400 years of Arctic climate change (Overpeck et al. 1997). Volcanoes, on the other hand, may have played a more important role compared to their influence on early Holocene warming. For example, the Greenland ice core indicates a strong correlation between reconstructed atmospheric volcanic sulfate loading and mean Arctic cooling (Zielinsky et al. 1994). This correlation suggests that volcanic eruptions entrain positive ocean feedbacks that enhance and prolong Arctic cooling (Overpeck et al. 1997). In addition, variability internal to Earth’s climate system also modulated climate over decades to
centuries. This is especially true of the Atlantic thermohaline circulation and the North Atlantic Oscillation (Chapman and Shackleton 2000), both of which influence the northward transport of heat from the tropics to the poles.

The Medieval Warm Period (MWP) is another centennial-scale climate event, which refers to a spatially variable period of relative warmth that preceded the colder temperatures of the LIA. Annually dated records encompassing the last 1000 years based on sediment and ice cores, as well as historical and tree ring data show early millennium temperatures as warm or warmer than the mid-20th century mean (Overpeck et al. 1997). This relatively brief period of warmth dates to approximately 800 AD to 1300 AD. Others have also reported a relative warming in the Canadian Arctic between 1000 AD and 1300 AD (Mober et al. 2005). Podritske and Gajewski (2007) report increased diatom concentrations, species richness, and organic matter in lake sediments from western Victoria Island during this period. In addition, similar high resolution, centennial-scale climate variations and associated ecological effects have been reported in other areas (Finkelstein and Gajewski, 2007). However, it remains important to note that temperatures were not anomalously warm at all sites during this period (Overpeck et al. 1997).

The high degree of spatial and temporal variation in the paleoclimatic records of the Canadian Arctic, especially at the centennial timescales, has contributed to a tendency to focus on the most robust trends that are clearly exhibited at the longer, millennial timescales (Kaufman 2004). However, studies of natural subdecadal to century-scale climate variability in the Canadian Arctic suggests that interannual to century-scale variability is the norm. The implications of this are that today’s Arctic cryosphere (glaciers and permafrost) as well as the biosphere (terrestrial, lacustrine, and marine) are not at steady state (Overpeck et al. 1997). This
means that certain physiographic features and ecosystems associated with the Canadian Arctic have, and will continue to change as the climate evolves.

Further documentation of the timing and spatial variability of Holocene climate and its impacts on ecosystems is required to better understand both the causes and potential impacts of climate change. While the Canadian Arctic is one of least disturbed regions on Earth, it is also one of the most susceptible regions to both natural and anthropogenic climate change (Overpeck et al. 1997). In addition to this, the Arctic climate is also an important factor influencing climates at lower latitudes. Therefore, the Canadian Arctic is an ideal place to investigate paleo-environments of the Holocene in an attempt to better understand the causes and effects of climate variations at multiple spatiotemporal scales.

1.4 Modern and paleoclimates from Melville Peninsula and adjacent regions

This section reviews differences in the timing and rates of Holocene paleoclimate change between sites to the immediate east and west of Melville Peninsula (the study site). I will first briefly discuss the Maxwell classification system (1980) of current climate regions with respect to the area around the study site, to provide a modern context for potential variations in the past climate regimes on Melville Peninsula.

Maxwell (1980) delineated five distinct climatic regions for the Canadian Arctic based on the study of major climatic controls such as atmospheric and ocean circulation, latitude, and surface albedo, as well as through examination of historical weather data. Many of these regions
consist of sub-regions, reflecting mesoscale climate variability ($10^1$ to $10^2$ km) in response to local topography, physiography and proximity to water or ice (Atkinson and Gajewski 2002).

Maxwell’s (1980) classification system places a major climate boundary in the Foxe Basin, separating the more maritime climates of the Baffin region (Region IV) from the more continental climates of the South-Central Arctic Archipelago (Region II) (Figure 1). The transitional climate associated with the vicinity of Melville Peninsula has been confirmed by more recent studies using modeled and interpolated climate data (Atkinson and Gajewski 2002). This boundary correlates with the maximum westward extent of the southerly cyclonic storm tracks that move northward through Davis Strait and Baffin Bay (Maxwell 1980). The specific location of the boundary between these two different climate regimes is likely influenced by local factors such as sea-ice regime, and therefore may shift on multiple temporal timescales.

Climate region IV, located to the east of Melville Peninsula, is the largest and most heterogeneous of the five zone delineated by Maxwell (1980). Cyclonic activity influences most of the region, which in combination with the presence of mostly first-year ice and persistently open water (polynyas), results in a lower annual temperature range than in most of Region II. Region IIa, located immediately to the west of Melville Peninsula, is marked by low relief, anticyclonic activity and a continental climate characterized by the second largest mean annual temperature range in the Canadian Arctic (~45°C), and very low annual precipitation (<100 mm) (Maxwell, 1980).

Melville Peninsula, including the study site, is located between these two climate zones in region IIb, which is transitional towards the more maritime climates of the eastern Arctic. This zone generally exhibits lower mean annual temperature range (36-39°C) and higher annual
precipitation (~200-300 mm) compared to region IIa to the west (Maxwell 1980). The location of the boundaries of the transitional climate associated with this region are likely influenced by sea-ice regime and the extent of summer open water and associated feedbacks with respect to the Foxe Basin to the east of Melville Peninsula.

The observed patterns of contemporary climate variability associated with the area around the study region (Melville Peninsula) presumably also existed in the past, and therefore must be considered in the interpretation of paleoclimatic records. A review of paleoclimatic records from the areas to the immediate east and west of Melville Peninsula reveals considerable differences in the timing and magnitude of climatic changes (Finkelstein et al. 2009).

Paleoclimate reconstructions from Boothia Peninsula, in Sub-Region IIa to west of the study site (Zabenskie and Gajewski 2007; Lamoureux et al. 2006), suggest that climatic shifts, such as the onset of Neoglacial cooling, and the timing of the LIA, occurred significantly earlier in this region when compared to sites on Baffin Island, in region IV to the east of the study site (Moore et al. 2001; Grumet et al. 2001; Joynt and Wolfe 2001). Available records also indicate a more variable climate during the past millennium in the Baffin region, with greater magnitude changes with respect to summer temperatures (Moore et al. 2001). Records from Boothia Peninsula, on the other hand, suggest relatively lower magnitude changes and a more stable climate during the past millennium (Zabenskie and Gajewski 2007). However, more well-dated, high resolution records are required to confirm these differences, and to better understand the spatiotemporal variability of Holocene paleoclimates with respect to the region around the study site.
A diatom study by Adams and Finkelstein (2010) from Melville Peninsula (the study site) provided evidence for a potential shift in the boundary of the continental/maritime climate zones, with the timing of paleoclimatic changes during the middle Holocene similar to reports from the Baffin region to the east, and the timing of late Holocene climate changes comparable to Boothia Peninsula to the west. However, uncertainty remains regarding whether the diatom record reflects a regional climate signal, or more local variations specific to the lake. Pollen analysis form this same site will help to fill in some of the gaps in the climate history of Melville Peninsula, by providing a record of the local and regional vegetation response to Holocene climate changes. Therefore, the results of my research may provide important new information on the changing boundaries between climate regions in the past, as well as new insights on the mechanisms that determine the location of such boundaries.
2 RESEARCH OBJECTIVES

The primary objective of this study is to provide a well-dated, high-resolution paleoenvironmental record for the study site by producing the first Holocene pollen diagram from Melville Peninsula. The Peninsula is of particular importance because of a lack of paleoenvironmental records, its location within a transitional climate zone, and its archaeological significance (Ross 2007; Finkelstein et al. 2009). Therefore, the results of this study will represent a step toward the goal of providing a network of sites from the Canadian Arctic that document Holocene climatic history. In addition these results may yield useful information for mapping shifts in the boundary between two important Arctic climate regimes. Finally, the potential sensitivity of the area, combined with a high-resolution pollen diagram, may permit documentation of paleoclimate variations at time scales relevant to current archaeological investigations that focus on the past 1000 years.

2.1 Key questions and expectations

1) How did terrestrial plant communities respond to post-glacial environmental changes at the study site?

It is expected that the sediment core obtained from Lake SP02, Melville Peninsula, will represent the time period from approximately 6500 yr BP to present, as the study site was not free of glacial ice until after this date (Dredge 2001). It will be important to determine the origin of all taxa identified from pollen analysis of the sediment core, in an effort to separate the long-distance component from the pollen originating at the study site, and on the Peninsula itself.
Sections of the core which show relative decreases in long-distance pollen, with synchronous increases in pollen concentrations, and the abundances of mid to low arctic taxa, such as Cyperaceae and \textit{Salix}, would provide strong support for periods of increased warmth and biological productivity (Gajewski 2002).

2) Does the pollen diagram from Lake SP02 show evidence for major climate variations documented at other sites across the Canadian Arctic, such as the HTM, LIA, or MWP?

The high temporal resolution (~150-250 years between samples) of the pollen diagram produced from Lake SP02 will permit investigations of environmental changes at multiple timescales. It will also be important to compare major Holocene climate fluctuations represented in the pollen diagram from Lake SP02 to similar studies from elsewhere in the Canadian Arctic. Such comparisons will provide important regional context for paleoenvironmental inferences with respect to the study site, by documenting how vegetation has responded to climate changes at various spatial and temporal scales.

3) How do these results compare to the published diatom record from the site?

Comparing the results of this pollen analysis with previously published diatom data from the same lake (Adams and Finkelstein 2010) will help to determine whether a climate signal is present in these records. Simultaneous fluctuations in both pollen and diatom concentrations would suggest changes in the productivity of both terrestrial and aquatic organisms, and could provide strong support for large-scale environmental change. However, disagreement between the pollen and diatom records could suggest a difference in the primary factors influencing these
two proxies, as well as provide important insights into the different responses of terrestrial and aquatic ecosystems to multi-scale climate variability.

4) How do the timing and rate of environmental changes for Melville Peninsula compare to study sites in adjacent climate regions?

Assuming that evidence is found for major Holocene climate changes, this study will allow for comparisons of the timing and duration of such events with adjacent Arctic sites. If the factors influencing climate variability at the sample site are similar to those at the regional scale, it is anticipated that timing of the onsets of these climate events will be later in time compared to sites to the west of Melville Peninsula due to lingering effects of the Laurentide Ice Sheet in the eastern Arctic (Kaufman et al. 2004).

5) What do these results suggest about the nature of paleoclimatic variability on Melville Peninsula since the last ice age, and what might be the primary mechanisms influencing such changes?

Due to the location of the study area within a transitional climate zone (Maxwell 1980), it is anticipated that timing and rates of Holocene climate changes will be intermediate to those documented for the areas immediately east and west of the Melville Peninsula. Lack of conformity to this expectation could suggest a shift in the boundary separating the more continental climate zones of the Canadian Arctic from those representing maritime climate regimes. Temporal variations in the position of such boundaries, are therefore expected to provide potential insights into the mechanisms that influence the position of major Arctic climate region.
3 STUDY SITE

3.1 Site description

The study site is located on Melville Peninsula, Nunavut, which is situated on the eastern Canadian Arctic mainland (Figure 1). Sarcpa Lake (68°33’ N and 83°17’ W, 220 m a.s.l.) is located approximately 100 km south-west of the community of Hall Beach (68°45’ N and 83°13’ W) on the eastern coast of the Peninsula. The lake flows into the larger Hall Lake to the east via the Kingora River. The area surrounding Sarcpa Lake is characterized by many ridges and valleys, with local relief ranging from 30 to 60 m a.s.l. Smaller lakes and ponds are also ubiquitous in the area. One such lake, unofficially named Lake SP02 (68°33’12.6” N and 88°17’26.5” W, 225 m a.s.l.) was selected for paleoenvironmental research (Figure 2). Lake SP02 is a relatively small and shallow lake, which has a surface area of approximately 3 ha and an estimated maximum depth of 16 m, as determined by point measurements at the site of sediment core extraction. The topography of the lake basin is steep-sided and non-uniform. While at the field site in mid-June 2008, the lake remained covered by approximately 2 m of ice, with a layer of slush on top.

3.2 Geology and physiography

Sarcpa Lake is located in the Central Plateau region, which is one of the six physiographic regions associated with Melville Peninsula (Dredge 1995). The area is characterized by Precambrian basement rock of the Canadian Shield, such as granitoid gneiss with crystalline silicates, and banded iron formations. The North-Central portion of the Central Plateau, where the sample site is located, is called the Central Till Plain, and is marked by gentle
rolling relief, glacial lake deposits, and outcroppings of granitic bedrock. This region extends from the Eastern Lowlands of the Foxe Basin to the Albert Hills to the north and west.

The surface deposits of Melville Peninsula are dominated by granitic till plains, which range in thickness from 1 to 10 m, and consist of stones with a silty sand matrix (Dredge 2001). Tills derived from carbonates in the northern portion of the plateau have a finer clayey silt matrix, while hummocky till blankets characterize the area to the west. Marine deposits consisting of deltaic sediments are common below 150 m a.s.l, and are represented by raised beach formations of sand and silt.

### 3.3 Glacial history

During the most recent ice age, the Melville Peninsula was completely glaciated by the Laurentide Ice Sheet (Dredge 2001). Evidence from the composition and distribution of carbonate till, glacial erratics, and sequences of striated bedrock suggest that two separate ice masses persisted on the Peninsula, with the Foxe Ice dome centered over the Foxe Basin, and a local ice mass located on the south-east portion of the Peninsula. The area around Sarcpa Lake, which includes the sample site, was covered by the Foxe Ice Dome, with the local ice mass extending just south of this region.

The timing of deglaciation and the extent of marine inundation on the Melville Peninsula was assessed by Dredge (1995) based on radiocarbon dates of marine deposits, in addition to striation patterns and the distribution of surficial landforms. Evidence suggests that net glacial ablation and ice retreat in the Foxe Basin began first in the south approximately 6,900 yrs BP, and progressed northward, as indicated by ice-contact marine deposits, washing limits, and
radiocarbon dates (Dredge 2001). Maximum postglacial marine submergence along the east coast of the Peninsula occurred approximately 6,500 to 6,900 yrs BP, with sea level 130 to 140 m above present level, and marine limits as far as 70 km inland. Marine deposits indicate that by 6,500 yrs BP, sea level had fallen to 120 m above present sea level, and that the Foxe Basin was completely ice free (Dredge 1995).

Radiocarbon dating of marine deposits suggest that the areas around the Kingora river and Sarcep Lake (including the study site) were completely ice free by 6,500 yrs BP (Dredge 2001). However, at this same time a remnant ice sheet of the regional Foxe Ice Dome persisted along the Eastern Lowlands between Hall Lake and Lailor Lake. Glacial landforms and radiocarbon dating suggest that this remnant ice sheet may have persisted as late as 5,500 yrs BP (Dredge 1995). Marine deposits indicate that the eastern coast of the Melville Peninsula may have remained submerged until 1,500 to 2,000 yrs BP, with an average rate of isostatic rebound over the course of the past 1,000 years of approximately 70 cm per century (Dredge 1995).

3.4 Vegetation

The Sarcep Lake region is classified as “graminoid tundra” and “barren” in the CAVM classification; these categories are typical in areas in the Arctic with exposed Canadian Shield bedrock (CAVM Team 2003). The graminoid tundra region is moist to dry with open to continuous vegetation cover, and percent surface vegetation cover ranging from approximately 30 to 90%. Predominant vegetation includes dwarf-shrub and forb tundra, such as prostrate Salix <30 cm tall, as well as herbaceous ground cover, including Cyperaceae, Cassioppe, Saxifragaceae, and Dryas. Although most of these taxa are ubiquitous across most Arctic regions, some taxa are
more abundant in the high-Arctic such as *Oxyria* and Poaceae, while other are more abundant in the middle-Arctic such as Cyperaceae (Gajewski 2002; Peros and Gajewski 2008). The barren region is void of vegetation cover, with the exception of orange and yellow lichens, and is comprised of exposed rocky outcrops and boulders.

### 3.5 Limnology

Melville Peninsula contains many freshwater lakes, ponds, rivers, and streams, which formed at the end of the last glacial period (Dredge 1995). Geochemical conditions of Arctic freshwater bodies are influenced primarily by the geochemistry of surface sediments and underlying bedrock (Wetzel 1983). Lakes and ponds associated with Precambrian bedrock, such as those found in the Sarcpa Lake region, are typically neutral to slightly acidic, with very low specific conductivity (Hamilton et al 2001). In addition, most Arctic aquatic systems are ultra-oligotrophic, with limited phosphorous and nitrogen inputs due to prolonged ice cover, low precipitation, and limited vegetation (Murray 1998). As a result, the majority of the annual nutrient supply to Arctic lakes and ponds occurs during the short growing season in summer, when increased solar radiation causes snow and ice at the surface to melt, resulting in overland flow inputs to surrounding freshwater bodies. The timing and rate of ice-cover melt also influence the thermal conditions of the lakes and ponds, with some becoming thermally stratified in summer due to relatively rapid ice loss, while others remain ice covered throughout the year.
3.6 Climate

The climate for the Sarcpa Lake region is typical of the Canadian Arctic and is very cold and arid, where the mean monthly temperature of the warmest month is less than 10°C (Environment Canada 2011). The study site is located within the cold polar tundra climate region, according to the modified Koppen climate classification system, and based on the distribution of vegetation, temperature, and precipitation. This climate zone is characterized by a non-mountainous landscape, extreme radiation deficit in the winter, and 24 hours of daylight in the summer. Instrumental weather records from 1977 to present from the community of Hall Beach report an average annual temperature of -14.1°C, with average temperatures below -20°C between the months of November and April. Average temperatures above 0°C occur during the summer months of June, July, and August. The average total annual precipitation at Hall Beach is 216.7 mm, with 102 mm of precipitation in the form of rain between the months of July and August, and the remaining 114 mm of precipitation in the form of snow between the months of September and June (Environment Canada 2011).
4 METHODS

4.1 Field methods

During the 2008 field season, several sediment cores were collected from Lake SP02 in the Sarcpa Lake region, Melville Peninsula, Nunavut, by Dr. Sarah Finkelstein, Dr. Konrad Gajewski, and fellow graduate student Jen Adams. This lake was selected because it exhibited properties conducive to the deposition and preservation of a good stratigraphic sequence. SP02 is a relatively small lake, which is deep enough to prevent freezing of the entire water column, yet shallow enough to allow for the collection of sediments using hand-operated sediment coring equipment. Only one small inflow via the Kingora River was observed. Therefore, much of the pollen input to the lake system is presumed to be aerial in origin. The sediment core from Lake SP02 analyzed in this study was previously analyzed for diatoms and biogenic silica (Adams and Finkelstein 2010).

While at the field site in mid-June, the lake remained completely covered by 2 m of ice, and several holes were manually augered. Sediment cores were collected from the ice surface using a 5 cm diameter Livingstone corer, which was lowered to the lake bottom using drive rods. The sediment was collected in 1 m segments referred to as drives, until an impenetrable surface presumed to be mineral contact was reached. The first drive was collected in a clear plastic tube fitted with a piston (Drive zero). Drive zero was kept upright at all times to preserve the sediment water interface, and the chronology of the top few centimeters. The uppermost 15 cm was extruded in the field in 0.5 cm increments using a custom built extrusion device, and stored in individually labeled sealable plastic bags. The remaining portion of the sediment core was extruded as one continuous core into PVC split tubes lined with aluminum foil and plastic wrap.
The aluminum foil was carefully labeled with arrows indicating the direction of the top of the cores. Small sediment cores were also collected using a Glew gravity corer (Glew 1991), and the entire length of these cores were extruded on site into clear plastic bags at 0.5 cm increments. Once transported back to the Paleoeecology Laboratory at the University of Toronto, all sediments were stored in a walk-in refrigeration unit at approximately 6°C.

The primary sediment core analyzed in this study has been named SP02-H4, which consists of two drives (DO and D1) for a total length of 104.5 cm. The sediment core was collected from the middle of the lake with a water depth of 11.5 m. Visual analysis of the core stratigraphy revealed a transition in the grain size and texture of the sediment matrix at about 71 cm depth, with sediments above this level exhibiting a silty/sand texture, and sediments below showing more of a clayey/silt texture, with inclusions of small pebbles (<2 cm).

In addition to the primary sediment core, the top 15 cm from an additional sediment core named SP02-H2-G2 was utilized for pollen analysis of the uppermost sediments, which had been depleted from SP02-H4-D0 during previous analyses of diatoms and activity of $^{210}$Pb. The two drives from SP02-H4 were split lengthwise in the lab using a thin steel wire and a palette knife. One half of the sediment core was utilized for analyses of diatoms, BSi, LOI, and MS, while the other half was used for radiocarbon dating and pollen analysis.
4.2 Chronology

**Lead-210 Dating**

The radioisotope $^{210}\text{Pb}$ is commonly used to date sediments of approximately 150 years in age or less (Michelutti et al 2008). $^{210}\text{Pb}$ has a half life of 22.3 years, and is produced as the result of a known process of radioactive decay (Faure and Mensing 2005). Radioactive $^{210}\text{Pb}$ produced in the solid earth is known as supported $^{210}\text{Pb}$, which is constantly being produced via this decay process. Unsupported $^{210}\text{Pb}$, on the other hand, is the term given to $^{210}\text{Pb}$ supplied by the atmosphere to surficial sediments. As lake sediments accumulate, older strata begin to exhibit signs of radioactive decay of $^{210}\text{Pb}$ compared to the surface sediments, which continue to receive inputs of $^{210}\text{Pb}$ from the atmosphere.

Assuming a constant rate of supply of $^{210}\text{Pb}$ from the atmosphere, and an exponential rate of decay, the profile of $^{210}\text{Pb}$ activity vs. sediment depth is expected to show an exponential slope. This is an important point because failure to conform to an exponential curve could suggest that alternate factors are influencing the deposition and decay of $^{210}\text{Pb}$ at the site, such as reduced atmospheric deposition of $^{210}\text{Pb}$ due to prolonged ice cover on the lake (Wolfe et al 2004).

Cores SP02-H4-D0 and SP02-H2-G2 were dated using the $^{210}\text{Pb}$ radioisotope dating method for the uppermost sediment sections. Bulk densities for each sample were calculated using the ratio of dry sediment weight (g) to wet sediment volume (ml). The sediment core was sub-sampled at 0.5-1-cm increments, and small aluminum trays were used to dry the samples over several days in an oven at 60°C. The dry sample weights were determined using an
electronic mass balance, then ground to a fine powder using a mortar and pestle, and transferred to a plastic 15-ml centrifuge tube for transport to an analytical lab.

A total of 18 samples from core SP02-H4-DO from between 0 and 16.5 cm sediment depth were analyzed for $^{210}$Pb activity (Adams and Finkelstein 2010). A total of 10 samples from SP02-H2-G2 from between 0 and 7.5 cm sediment depth were also submitted for $^{210}$Pb analysis. Between 2 and 5 ml of wet sediment volume was required to achieve a dry sediment weight of 0.8 to 1.8 g. All samples were sent to Flett Research Ltd., Winnipeg, Manitoba for analysis of $^{210}$Pb. A constant rate of supply (CRS) model was applied to the $^{210}$Pb chronology, which assumes a constant rate of supply of $^{210}$Pb, while taking into account variations in sediment accumulation. The predicted sediment accumulation rate based on a linear regression model of $^{210}$Pb activity vs. cumulative dry weight (g/cm$^2$) was compared to the accumulation rates predicted by the CRS model to ensure that the latter was functioning correctly.

**Radiocarbon Dating**

Radiocarbon dating is based upon measurements of the decay of radioisotope $^{14}$C, which is present in the tissues of all organic matter (Williams et al 1998). Following death, the amount of $^{14}$C in the tissues of an organism decays according to a half-life of 5,730 years (Faure and Mensing 2005). Therefore, measurements of $^{14}$C decay in organic matter, once calibrated, can be used to provide an estimate of the amount of time since that organism expired. The application of radiocarbon dating methods to Arctic lake sediments is made difficult by the fact that there are typically very low concentrations of organic material in the sediments of ultra-oligotrophic Arctic lakes. Materials such as the remains of aquatic plants and animals, as well as bulk
sediment samples can be used for radiocarbon dating, but the most suitable material is considered to be terrestrial macrofossils (MacDonald et al 1991).

A total of six samples from core SP02-H4 were submitted to Beta Analytic Inc., Miami, Florida for Accelerated Mass Spectrometer (AMS) radiocarbon dating. The AMS method allows for improved accuracy and decreased sample size, relative to conventional methods. Organic material was recovered from 4 different sections of the core, at 20, 37, 57, and 77 cm, with a replicate sample from each of the last two levels. The two lower levels contained macroscopic organic material, including small leaves, seed pods from the genus *Salix*, twigs, stems, and seeds. The two upper levels did not contain any macroscopic organic matter, and therefore, smaller fragments of plant remains and chitinous material, such a chironomid head capsules, were picked using forceps after passing samples through a 90-µm sieve. Samples were viewed under a Zeiss Stereo Discovery V8 and Olympus SZ61 microscopes at 20x or 40x magnification. Once a minimum of 25 mg of organic material was retrieved for each level, the samples were transported to Beta Analytic Inc. in small plastic vials. Special care was taken during each step of this process to ensure that the samples were not contaminated by foreign carbon.

Calibration of conventional radiocarbon ages to calendar years was performed using the INTCAL04 database and the software CALIB v5.0.1 (Stuiver and Reimer 1993). All dates are expressed as “yr BP”, and refer to calibrated, calendar years before AD 1950. The age-depth curve for the lake sediment core SP02-H4 was established by linear interpolation between the $^{210}$Pb and $^{14}$C dates.
4.3 Geochemical analysis

*Magnetic Susceptibility*

Magnetic susceptibility (MS) refers to the degree to which sediments can be magnetized when exposed to a weak magnetic field. In general, the MS of a sediment sample is directly proportional to the amount, size, and orientation of magnetic minerals (e.g., magnetite) present in the material. Therefore, relative increases in the MS values of a sediment core are often interpreted as periods of increased mineral erosion of the surrounding watershed (Thompson et al 1975).

Measurements of MS for sediment core SP02-H4 were taken using a Bartington magnetic susceptibility meter and MS2E sensor. The sediment core was removed from refrigeration approximately 16 hours prior to analysis to allow for the material to reach room temperature. Special care was taken to ensure that there were no sources of electrical or metal contamination, including electrical outlets, metal tables, measuring tapes, and aluminum foil. All MS values are expressed in SI units, and the numerical setting on the meter was set to the x0.1 range, which is often reserved for weakly magnetic material.

Sediment core SP02-H4 was measured for MS continuously at 1-cm increments between 16.5 and 101.5 cm depths, as the upper section of this core was extruded in the field. The sensor was first calibrated by taking an air reading and then setting the meter to zero. With only a sheet of plastic wrap between the sediments and the sensor, the device was held against the sediment core until a consistent value was reached. After each measurement, the meter was again calibrated to zero by taking an air reading. Each 1-cm section of the sediment core was
measured in duplicate, and the final MS value for each depth was calculated as the mean value of the two readings taken at each section.

**Loss on Ignition**

Loss on ignition (LOI) is a commonly used method for measuring variations in the fraction of organic and inorganic carbon in sediment cores (Dean 1974). Results from LOI analysis for paleoenvironmental studies are often interpreted as reflecting variations in the organic matter and biological productivity of the lake (Adams and Finkelstein 2010), as well as of the surrounding watershed (Peros and Gajewski 2008). The sediment core SP02-H4 was subsampled continuously using a 1-ml extraction tool at 1-cm intervals along the length of the core. Sequential LOI was conducted following the method proposed by Heiri et al. (2001). Each sample was weighed using a digital mass balance prior to being dried at 105°C until an absolute weight was reached (24-36 hours). Following dehydration, the samples were cooled to room temperature and the weight of each sample was again obtained. The percent weight loss following ignition at 105°C (LOI105) is calculated as LOI105 = 100(WS – DW105)/WS, where WS is the weight of the sample before dehydration, and DW105 is the dry weight of the sample after being heated at 105°C. LOI105 is therefore a measure of the percent moisture content of each sample.

The samples were then ignited at 550°C for 4 hours, at which temperature organic matter is oxidized to CO₂ and ash (Heiri et al. 2001). The percent weight loss following ignition at 550°C (LOI550) is calculated as LOI550 = 100(DW105 – DW550)/ DW105, where DW105 is the dry weight of the sample after being heated at 105°C, and DW550 is the dry weight of the sample after being heated at 550°C. LOI550 is thus an estimate of the percent organic matter content.
During the final ignition phase, the samples were heated at 950°C for 2 hours, at which temperature CO₂ is evolved from carbonate, leaving behind oxide (Heiri et al. 2001). The percent weight loss following ignition at 950°C (LOI₉₅₀) is calculated as \( \text{LOI₉₅₀} = \frac{100(DW₁₀₅ - DW₉₅₀)}{DW₁₀₅} \), where DW₁₀₅ is the dry weight of the sample after being heated at 105°C, DW₅₅₀ is the dry weight of the sample after being heated at 550°C, and DW₉₅₀ is the dry weight of the sample after being heated at 950°C. LOI₉₅₀ is an estimate of the percent carbonate content of each sample. Following ignition at 950°C, the remaining sample is referred to as residuum (LOIres) and is calculated simply as \( \frac{DW₉₅₀}{DW₁₀₅} \).

Care was taken following each burn to ensure that all samples remained covered and that they were cooled to room temperature prior to determining the weights in an effort to minimize error in LOI determination. Average cooling time ranged from 30 to 40 minutes in an air conditioned laboratory without the use of a desiccator. All LOI values are expressed here as a percentage of the dry sample weight. An exception is LOI₁₀₅, which as a measure of moisture loss is expressed as a percentage of the wet sample weight.

4.4 Pollen methodology

Counting and identifying pollen in Arctic sediments of low concentration is extremely time consuming, thereby limiting the number of samples and the temporal resolution of the resulting pollen diagram (Gajewski et al 1995). In an attempt to improve pollen recovery, a method of heavy liquid separation using Sodium Polytungstate (SPT) was employed in this study. Although heavy liquid separation has been used previously by some pollen laboratories (Bolch 1997; Kerstholt 1995; Skipp and Brownfield 1993; Traverse 1988), it was the study of
lake JR01 on Boothia Peninsula, Nunavut by Zabenskie and Gajewski (2007) that first used SPT to separate pollen from the sediment matrix in studies of post-glacial lake sediments in the Canadian Arctic, and to offer a detailed protocol for this procedure. By systematically testing the results of the SPT method against the more standard method using Hydrofluoric acid (HF) digestion, the authors were able to demonstrate that there was no significant difference in the number and types of pollen taxa recovered. Furthermore, the SPT method was proven to successfully remove more of the extraneous sedimentary material from the sample when compared to the HF method, which allows for an increase in the number of pollen counted per unit of time (Zabenskie and Gajewski 2007).

The method for processing lake sediment samples for pollen analysis used in this study is described below, and follows the method described by Faegri and Iverson (1998), with modifications introduced by Zabenskie and Gajewski (2007). Also included are modifications that I have made based on personal communications with Matthew Peros at the Laboratory of Paleoclimatology and Climatology (LPC) at the University of Ottawa, and first-hand experimentation. A total of 29 samples were processed for pollen, including 24 samples from sediment core SP02-H4-D0 between 10 cm and 71 cm sediment depth, 4 samples from sediment core SP02-H2-G2 between 2.5 cm and 9 cm sediment depth, and a surface sample from SP02-H2-G1. All samples were processed at the Paleoecology Laboratory at the University of Toronto according to the methods described here, with the exception of the surface sample which was processed by Konrad Gajewski at the LPC in Ottawa.

1) Between 2.5 ml and 4 ml of wet sediment were sub-sampled from the sediment core and placed in sterilized 50-ml disposable centrifuge tubes. For the majority of the samples, 4
ml of sediment was used to maximize the amount of pollen recovered. Tubes were labeled, and all notes were recorded in a lab book using the standard template.

2) Two tablets of Lycopodium spike (for a total of 37,168 spores) were added to each tube, with the batch number and number of spores noted.

3) About 10 ml of 10% Hydrochloric acid (HCl) was added to each sample to dissolve the Lycopodium tablets and any carbonate in the sediment. Once fizzing had stopped, each sampled was stirred with a wooden stir stick to remove any clumps.

4) Each tube was capped, balanced, and placed in the centrifuge for 5 minutes at 4000 rpm. Once finished, the supernatant from each tube was decanted into the acid waste container.

5) A wash was performed by adding approximately 40 ml of distilled water to each tube. Each sample was then stirred, balanced, capped, centrifuged, and decanted.

6) Approximately 40 ml of 10% Potassium Hydroxide (KOH) was added to each tube, which were then stirred and placed in a boiling water bath for 15 minutes. Wooden stir sticks were not left in the tubes during the water bath process to ensure that the samples would not be contaminated.

7) Step 5 was repeated, in some cases twice, to wash the samples of any remaining KOH, and to prevent any excess particulates from floating in the tubes. During each wash, a squirt of ethanol was added to each tube to break the surface water tension, which may cause pollen to become trapped in the meniscus. Also, special care was taken to decant as much water from each tube as possible, to avoid potential dilution of the SPT during heavy liquid separation.
8) In some cases, an additional rinse with 10% HCl was performed at this stage, as there is evidence to suggest that acidification of the sample prior to heavy liquid separation may improve pollen recovery (Zabenskie and Gajewski 2007).

9) The Sodium Polytungstate (SPT) solution was made by dissolving SPT powder in distilled water. A hydrometer was used to measure the relative density of the solution, where a specific gravity of 1.95 was required to allow the pollen to float in solution, as sporopollenin has a specific gravity of approximately 1.4 (Zabenskie and Gajewski 2007). The inorganic component of the sediment matrix, on the other hand, typically has a specific gravity of over 2.0. Therefore, the addition of the SPT heavy liquid to each sample is intended to allow the pollen to float and become suspended in the solution, while the extraneous sediment component remains at the bottom of each tube.

10) 8 ml of the SPT solution was added to each tube, and the samples were then agitated in a vortex at the maximum setting for at least 5 minutes. This step is extremely important as failure to adequately agitate each sample could result in unrecovered pollen which remains associated with the heavier sediment components.

11) Once vortexed, each sample was balanced, capped, and centrifuged at 1800 rpm for 10 minutes. The speed of the centrifuge was decreased from the typical 4000 rpm to ensure that pollen was not forced down the bottom of the tubes. Also, each centrifuge bucket had to be balanced with extra tubes filled with water, as additional SPT could not be added to any of the samples.

12) After centrifuging, the supernatant from each tube, which in this case contains the pollen sample, was decanted into a new labeled 50-ml tube. Some of the pellets which remained in the original tubes were analyzed for unrecovered pollen by making a smear slide. In
all cases, no significant amounts of pollen were observed in the post-SPT pellets, and the remainder of these pellets were therefore discarded. These original tubes were then thoroughly cleaned with distilled water.

13) The cleaned original tubes, in combination with the new tubes that now have the SPT solution and pollen sample, were used to divide each sample in half. The reason for splitting each sample between two tubes is to reduce the volume of SPT in each tube to allow for maximum dilution of the heavy liquid solution. It is important to reduce the density of the solution to a specific gravity below 1.4 to allow the pollen in each sample to once again sink to the bottom of the tube. Each tube was filled as high as possible with distilled water and a squirt of ethanol, and then centrifuged at 4000 rpm for 5 minutes.

14) The used and diluted SPT from each tube was then decanted into a container. The used SPT was later filtered using 2 coffee filters, and a Buchner funnel with a 9 µm mesh. The filtered solution was then allowed to evaporate inside a fumehood until a specific gravity of 1.94 was again reached for future use. This method of recycling the SPT solution reduced the time and cost of having to make a new batch of the solution every time.

15) Each of the two tubes containing the pollen sample were then combined into a single tube using distilled water and a squirt of ethanol, centrifuged, and decanted.

16) At this point, it was decided that the use of HF was not necessary as the samples were not excessively silty, and the use of this acid is extremely dangerous.

17) Each sample was placed through a 10 µm and 90 µm sieve in an attempt to remove any remaining material that was not within the size range of pollen from typical Arctic taxa. A plastic make-shift sieve was fashioned from a small Tupperware container. Following
sievıng through a 10 mesh, the material that did not pass through was recovered using a squırt bottle of distilled water, and was poured back in the centrifuge tube. Following sievıng through the 90 µm mesh, only the material that passed through the sieve was recovered for further processing. In each case, distilled water was added to the samples, and for the 10 µm mesh an electric engraver was used to agıtate the samples while in the sieve. This helped to promote the flow of the sample through the sieve. Each sample was then washed, centrifuged, and decanted.

18) Excess water was removed from each sample prior to acetolysis by adding a half tube of Glacial Acetic acid. Each tube was then stirred, balanced, capped, centrifuged, and decanted.

19) The acetolysis solution was prepared by very slowly adding one part Sulphuric acid to 9 parts Acetic Anhydride. This was done in a clean and dry graduated cylinder using a pipette, inside the fumehood.

20) Each tube was then filled approximately half way with the acetolysis solution and placed in a boiling water bath for 3 minutes. The samples were then carefully removed from the bath, stirred, balanced with Glacial Acetic acid, capped, centrifuged, and decanted.

21) A half tube of Glacial Acetic acid was again added to each tube to rid the samples of any remaining acetolysis solution. Each tube was stirred, balanced, centrifuged and decanted.

22) A wash step with distilled water was then performed as described in step 5.

23) A half tube of Tertiary Butanol alcohol (TBA) was added to each sample, along with 2 drops of safranin stain. The samples were then stirred, centrifuged and decanted.
24) The samples were then transferred to small glass vials using a squirt of TBA. The samples were balanced, centrifuged, and decanted. Each vial was carefully labeled, and wrapped in clear tape to ensure that the ink would not be dissolved by the alcohol.

25) A couple drops of silicone oil were added to each of the samples, which were then thoroughly mixed using a wooden stir stick. The vials were then left open in the fumehood overnight to allow for any excess TBA to evaporate. Vials were then sealed with a cork plug and kept upright during storage.

To identify and count pollen, a small aliquot of the residue contained in the sample vial was placed onto a glass slide for each level of the sediment core sub-sampled, with multiple slides prepared for each level. An 18 by 18 mm glass cover slip was then placed onto the slide and secured using a small amount of nail polish in each corner. The slides were then stored upright to ensure that the mounted sample stayed centered on the slide. Pollen were counted using a Zeiss light microscope, and an Olympus compound microscope, at 400x magnification. For critical identifications, 1000x oil immersion magnification was used. In each case, the entire slide was covered using 0.5-mm transects. Pollen was identified using the pollen reference collection at the Paleoecology Laboratory at the University of Toronto, in addition to literature containing photos and descriptions of pollen associated with relevant taxa (Kapp 2000; McAndrews et al 1973).

The total number of pollen counted at each level (pollen sum) was at least 200 grains in most cases. For some levels this sum was not reached due either to an inadequate concentration of pollen, or due to poor recovery of pollen. A minimum of 300 grains is more typical of pollen studies, but the low concentrations of pollen in Arctic settings make such sums overly time consuming. Also, the relatively limited diversity of Arctic taxa (<20) means that the pollen sums
typical of most pollen studies should not be necessary to reconstruct an accurate fossil pollen assemblage (Zabenskie and Gajewski 2007).

To test whether a pollen sum of 200 grains was sufficient, data were collected for each level on the number of taxa identified relative to the number of grains observed (Table 4). These data indicate that in all cases the maximum species richness was obtained well below a pollen sum of 200 grains, and in most cases the maximum number of taxa were observed with a pollen sum of only ~110 palynomorphs. Therefore, it was determined that a pollen sum of 200 palynomorphs for each level was sufficient to accurately estimate the relative percent abundances of the fossil taxa. These pollen sums do not include observations of broken, unidentified, or unknown polymorphs, and are based on counts of both long distance and local/regional pollen.

4.5 Data analysis

Pollen concentrations were calculated using the following formula: \( \frac{(P_0 \times L)/L_0}{V_s} \), where \( P_0 \) is the number of palynomorphs observed, \( L \) is the number of *Lycopodium* spores added to the sample, \( L_0 \) is the number of *Lycopodium* spores observed, and \( V_s \) is the volume (cc) of wet sediment sub-sampled. Total pollen concentrations were calculated using the sum of all palynomorphs, including long distance, regional, local, and unidentified pollen, as well as spores. Long distance pollen concentrations were calculated using only the sum of long distance pollen for *Pinus, Picea, Alnus,* and *Betula.* Local and regional pollen concentrations were calculated using all taxa, except for long distance taxa, spores, and unidentified pollen grains, which were removed.
In an effort to save time, and increase the total number of pollen counted at each level, only 100 *Lycopodium* spores were counted for most levels. The number of palynomorphs observed was noted at this point, and used as the $P_o$ variable in the concentration calculation (as opposed to the total pollen sum). However, the relative proportions of long distance and local/regional pollen were not noted at the time that 100 exotic spores were observed. As a result, the total pollen sums for both long distance and local/regional pollen assemblages were used in the calculations of these respective pollen concentrations. Therefore, the total pollen concentration, and the long distance and local/regional concentrations cannot be directly compared in terms of absolute values, and are intended for comparisons of variance through time only. This is also the case with the pollen accumulation rates, which were calculated by multiplying the pollen concentration by the sediment accumulation rate (SAR), as determined by linear interpolation of the $^{210}$Pb and $^{14}$C data.

ZONE software was used to identify potential major shifts in the fossil pollen assemblage through time. Local and regional pollen counts were converted to percentages, and the data were not transformed. The long-distance pollen component was removed, as well as spores and unidentifiable palynomorphs, so that the pollen zones would be better suited to inferences of changes in the local and regional vegetation for the study site. The algorithm used to identify potential zones was SPLITSLSQ algorithm, which is based on an unweighted least squares cluster analysis (Birks and Gordon 1985). Like the commonly used CONISS algorithm (Grimm 1987), SPLITSLSQ also uses a sum of squares to identify groups in the dataset. The advantage of SPLITSLSQ in this case is that unweighted least squares analysis is better suited to datasets with very low proportions of most taxa.
5 RESULTS

5.1 Chronology

Sediment core SP02-H4 has a total length of 106 cm. Results of $^{210}$Pb analysis from this core reveal a somewhat irregular, but generally exponential drop in $^{210}$Pb activity as a function of depth (Figure 3). The $^{210}$Pb background appears to have been achieved at depth 4 - 4.5 cm (2.29 DPM/g) (Table 1). The maximum activity of 30.94 DPM/g seen in the surface section is approximately 14 times the assumed background level. The sediment accumulation rates range from 0.0050 to 0.0156 g/cm$^2$/yr, assuming a constant rate of supply of $^{210}$Pb (CRS model).

A Glew core (SP02-H2-G2) was also analyzed for $^{210}$Pb, as the upper 7.5 cm of sediment core SP02-H4 did not have enough sediment remaining for pollen analysis. The $^{210}$Pb results for SP02-H2-G2 also show an approximately exponential decrease in $^{210}$Pb activity as a function of depth (Figure 3). The $^{210}$Pb background of 2.61 DPM/g appears to have been achieved at depth 5.5 cm, with maximum levels at depth 0-1 cm, 7 times the background level at the lowest section (Table 2). The sediment accumulation rates vary between 0.0051 to 0.0090 g/cm$^2$/year. In both cores, estimates of ages greater than 80 years are considered to be approximations only.

These results suggest that the sediment accumulation rates for these two adjacent cores from Lake SP02 are very similar (0.0050 to 0.0156 g/cm$^2$/yr). In addition, $^{210}$Pb activity in both cores reaches background levels of 2.29 to 2.61 DPM/g between 4.5 and 5.5 cm depth. The oldest non-extrapolated age estimates from sediment cores SP02-H4 and SP02-H2-G2 are both from the 3.5 cm section (Tables 1 and 2), at 121 and 159 years BP respectively. Due to the similarity of the $^{210}$Pb decay curve from these two cores, it is appropriate to apply the chronology
based on the $^{210}$Pb dates from the upper sections of SP02-H4 to the stratigraphic pollen analysis of SP02-H2-G2.

Four AMS radiocarbon dates from SP02-H4 were used to construct an age model (Figure 4; Table 3). The chronology established for this core is based on linear interpolation between each of the four radiocarbon dates, and the lowermost $^{210}$Pb date. All dates are reported using the notation “yr BP”, referring to calibrated years before AD 1950. One sample from 57 cm depth was excluded from the age model (Table 3), as it yielded a very old age estimate of 8630 to 9010 yr BP. This age estimate is considered anomalous, as there is strong evidence to suggest that the study site was glaciated during this time (Dredge 2001). Therefore, this date was rejected, and the sample was not included in the age model. A possible explanation for this unusually old age estimate is potential contamination of the sample from ancient carbon associated with carbonate till deposits near the study site (Dredge 1995). Supporting this explanation is a relative peak in the magnetic susceptibility values (Figure 5) at approximately 57 cm depth, which suggests increased erosion of material from the watershed.

The age depth model was not extrapolated beyond the lowermost radiocarbon date of 6630 yr BP, as evidence from radiocarbon dates associated with glacial landforms on Melville Peninsula suggest that deglaciation in the study region did not commence until approximately this same time period (Dredge 2001).
5.2 Magnetic susceptibility

Magnetic susceptibility (MS) results from sediment core SP02-H4 (Figure 5), based on the mean value of a total of 81 duplicate samples, show a brief increase to 147.3 SI at 71 cm depth (6350 yr BP), followed by a pattern of general decrease for the remainder of the record. There is a rapid decline in MS values between 6350 to 5300 yr BP, with levels dropping to below 20 SI. There is also relatively greater variability in MS values observed for this period, compared to the latter part of the record. For the period 5300 to 1455 yr BP, MS values gradually decrease with very little fluctuation, to a minimum of 3.65 SI at 18.5 cm (1670 yr BP).

5.3 Loss on ignition

Results from LOI550, as a method for estimating the percent organic matter of a sediment sample, indicate very low values of ~3% in the lowermost section of sediment core SP02-H4 at 71 cm (6350 yr BP) (Figure 5). Organic matter generally increases, to a maximum of 9-11% between 4440 and 2980 yr BP. Following this period, the LOI550 profile shows a decreasing trend, until minimal values of ~3% are again observed at approximately 810 yr BP.

Estimates of carbonate content are based on LOI950, and exhibit maximum values of ~5% at 6350 yr BP, followed by a rapid decline to ~1% by 6100 yr BP (Figure 5). Values remain at very low levels throughout the remainder of the record, with very little variation. Unfortunately, duplicate samples were not possible for measurements of LOI550 and LOI950. As a result, estimates of organic matter, and carbonate content are reliable to only 0.001 g, as fluctuations in sediment weight on the order of 0.0001 g were common due to tiny additions of atmospheric moisture to the dry sediment sample following ignition. Therefore, steps were taken to minimize
this error, as described in the methodology section, by keeping all samples covered during the cooling phase, and by standardizing the timing and manner in which the sample weights were obtained.

5.4 Fossil pollen assemblages

A total of 29 samples were analyzed for fossil pollen, with four samples between 2.5 and 9 cm depth (about 10 to 600 yr BP) from sediment core SP02-H2-G2, and the remaining 25 samples from core SP02-H4 between 10 and 71 cm (about 810 to 6300 yr BP) (Appendix A). The only exception is the surface sample (0-1 cm), which is from sediment core SP02-H2-G1, and processed by Konrad Gajewski at the Laboratory for Paleoclimatology and Climatology at the University of Ottawa. Unfortunately, the amount of sediment processed for the surface sample proved to be inadequate (1.1 cc), and the heavy liquid separation technique failed to remove a significant fraction of non-pollen material. As a result of the poor recovery and low concentration of pollen for this level, a pollen sum of only 19 was achieved for the surface sample. Total pollen sums for the remainder of the record range between 171 and 271 palynomorphs, with an average of 205 per level. Another exception is the sample from 14.5 cm depth where an anomalously low pollen sum of 94 was reached. The total pollen concentration for this level (Figure 5) is not particularly low, and it is therefore likely that the majority of this sample was decanted and lost during processing in the laboratory.

A total of 26 taxa were identified in the record, with the maximum number of observed taxa at any one level (species richness) ranging from 9 to 19, with an average of 15 taxa per level (Table 4). The total pollen sum required to achieve maximum species richness ranged from 40
to 160, with an average pollen sum of 112 for each level. Pollen counts beyond this sum did not produce any novel taxa, and it was therefore determined that a total pollen sum 200 palynomorphs per level was sufficient to accurately reconstruct fossil pollen assemblages at the study site.

Dominant local and regional taxa include Cyperaceae, Ericaceae, *Artemisia*, *Salix*, and *Oxyria* (Figure 6). Cyperaceae is by far the most dominant taxon, with relative abundances of 30-50% for the majority of the record. Other dominant local and regional taxa are typically less than 10%. All other herbaceous ground cover plants show relative abundances of less than 2%. For a complete list of taxa see the raw pollen counts in Appendix A. Dominant long distance taxa, including *Pinus*, *Alnus*, and *Betula*, which show relative abundances that generally range between 10-20% for the majority of the record (Figure 6).

Total pollen concentrations were calculated using all taxa, with a mean value of about 9400 grains/ml and a range of approximately 1800 to 50,000 grains/ml (Figure 5). Concentrations are generally low (less than 10,000 grains/ml) in the lowermost (6300 to 5300 yr BP) and uppermost (1200 yr BP to present) sections of the record, with maximum values observed between 5000 and 2600 yr BP.

Total pollen accumulation rates range from 18 to 940 grains/cm²/yr, with an average of 127 grains/cm²/yr. The total pollen accumulation profile exhibits a pattern similar to total pollen concentrations, with minimal values of less than 30 grains/cm²/yr in the bottom section of the record at 6300 yr BP, followed by a general increase towards maximum values at 4400 yr BP, relative increases 3200 and 1200 yr BP, and generally lower values for the remainder of the record. One exception is the high pollen accumulation rate observed during the 20th century (940
grains/cm²/yr), which is a pattern not present in the total pollen concentration values (Figure 6). Long distance pollen accumulations range between 26 to 178 grains/cm²/yr, showing maximal values in the lowermost sections of the core (6300-5300 yr BP), and generally decrease for the remainder of the record, with notable increases at 4500 yr BP and in the uppermost sections representing the 20th century. Local and regional pollen accumulations are relatively higher compared to the long distance component, and range between 35 to 487 grains/cm²/yr. The profile of the local and regional pollen component remains relatively stable for the majority of the record, with increased accumulations at 4500 yr BP and after 1000 yr BP (Figure 6). The absolute values of long distance and local/regional pollen accumulation rates cannot be directly compared to the total pollen accumulations due to differences in calculations described in the methodology section.

Four pollen zones were produced based on the SPLITSLSQ algorithm (Birks and Gordon 1985) using unweighted least squares analysis cluster of local and regional pollen abundances (Appendix B). Abundances of long distance pollen and spores were not included, to facilitate observations of changes in the vegetation associated with the study site. Although 10 zones were chosen as the predetermined number of groupings for the ZONE output, only 4 of the most well defined zones were accepted, with pollen Zone 4 consisting of three sub-zones (4a, 4b, and 4c). Some proposed zones were rejected due to a low level of dissimilarity with adjacent zones, or when the zone included only one sample. Proposed zones were also rejected where an inadequate pollen sum was achieved, as was the case for the surface sample (Appendix B). These zones are expected to aid in the interpretation of the pollen diagram, and will be used to discuss the vegetation history of the study site.
Zone 1: 6300 to 5900 yr BP (71-62.5 cm)

Pollen Zone 1 is represented by the bottom-most section of the record, and is comprised of 3 samples (Figure 6). During this period the percent abundance of *Alnus* pollen is highest for the entire record at over 40%, and exhibits a decreasing trend. *Betula* also shows maximal values at about 10%, and remains stable, while *Pinus* has the lowest abundance of the record at approximately 5%. All local and regional taxa exhibit minimal percentages during this period, with the exception of *Salix* and *Artemisia*, which show maximum values of more than 10%. At the beginning of this period, Cyperaceae abundances are very low at less than 10%, and although an increasing trend is observed for this taxon, values remain at less than 20% for the remainder of Zone 1. Total pollen concentrations are greater than 10,000 grains/ml, with total pollen accumulation rates between 100-200 grains/cm²/yr.

Zone 2: 5900 to 5300 yr BP (62.5-52.5 cm)

Pollen Zone 2 is characterized by an increase in *Pinus* to nearly 20% abundance (Figure 6), while *Alnus* and *Betula* are relatively less abundant compared to the preceding period. Cyperaceae shows a sharp increase to almost 30%, with *Sphagnum* also increasing to nearly 20% (the highest in the record). *Artemisia* and *Salix* are relatively less abundant with values less than 10%. Total pollen concentrations and accumulations show relative decreases compared to the preceding period, but generally remain stable throughout Zone 2.

Zone 3: 5300 to 3900 yr BP (52.5-35.5 cm)

During pollen Zone 3 (Figure 6), abundances of *Pinus* and *Betula* show considerable fluctuation, although the overall trends during this period are neither increasing nor decreasing.
Alnus, on the other hand, declines from more than 25% to less than 15%. Abundances of local and regional herbs, such as Cyperaceae, Ericaceae, and Artemisia, show an increasing trend during this period, with abundances of Cyperaceae reaching as high as approximately 50%. Sphagnum also exhibits a pattern of general increase, although relative abundances are less than the preceding period. Total pollen concentrations and accumulations show a significant increase, as well as the long-distance pollen accumulations although to a lesser extent. However, one must be cautious when interpreting the increases in pollen concentrations and accumulations in this case, as they are based on a single sample point.

Zone 4a: 3900 to1300 yr BP (35.5-15.5 cm)

Pollen Zone 4 has been split into three subzones (a, b, and c), as the separation of these groups based on unweighted least squares cluster analysis of the local and regional pollen abundances was not as distinct compared to the first three zones (Appendix B). In Zone 4a (Figure 6), the relative abundances of both Oxyria and Ericaceae increase, although both remain at less than 5%. Alnus and Betula exhibit an overall decline during this period. Pinus abundances fluctuate considerably, but the general trend for this taxon is one of increase for this period, with values reaching over 25%. Cyperaceae shows a decreasing pattern during the first half of Zone 4a, although values by the end of this period are comparable to Zone 3, at approximately 50%. Trends in the total pollen concentration and accumulations are inversely proportional to Cyperaceae during this period, with relative increases at approximately 2500 yr BP.
Zone 4b: 1300 to 1000 yr BP (15.5-12.5 cm)

Pollen Zone 4b represents the shortest time period identified in the record (Figure 6). This zone is characterized by brief increases in *Pinus* at nearly 40%, and *Picea* at about 5% (highest for the record), as well as slight increases in Poaceae, Ericaceae, *Artemisia*, and *Potentilla*. Total pollen concentrations and accumulations also exhibit relative increases at the onset of this period. Cyperaceae and *Sphagnum*, on the other hand, show relative decreases during this time.

Zone 4c: 1000 yr BP to present (12.5 – 0 cm)

Pollen Zone 4c is the final zone identified for this record (Figure 6), which is marked by a rapid decline in the abundance of *Pinus* to about 10%, with *Artemisia* and total pollen concentrations also showing a pattern of general decline. Conversely, relative abundances of *Alnus*, *Betula*, Cyperaceae, *Salix*, and *Sphagnum* all show increasing trends during the first half of Zone 4c, although *Alnus*, Cyperaceae, Poaceae, and *Sphagnum* decrease during the latter portion of this zone, corresponding to approximately the past 300 yr BP. Therefore, variations in the relative abundance of *Salix*, which increases from 0-1% at about 1000 yr BP to 5-7% at present day, is considered to provide the clearest signal of recent environmental change for this period. All other local and regional taxa remain relatively stable, with very low abundances of less than 2%. In addition, all of the pollen accumulation rates show significant increases in the uppermost sections of the sediment core.
6 DISCUSSION

Documentation of the vegetation history for the study site since deglaciation of Melville Peninsula (~6500 yr BP) is important to better understand how local and regional vegetation responded to changing environmental conditions during the Holocene. Discussion of the pollen record produced for Lake SP02 is organized with respect first to the middle Holocene (6300 to 4000 yr BP), followed by the late Holocene (3900 yr BP to present).

6.1 Vegetation history

*Middle Holocene (6300 to 4000 yr BP)*

The middle Holocene is comprised of pollen Zones 1 to 3, and covers the period from about 6300 to 4000 yr BP (Figure 6). Local and regional pollen identified in Zone 1 (6300-5900 yr BP) is considered to represent pioneer vegetation, as there is strong evidence to suggest that the study site was glaciated up until the beginning of this period (Dredge 2001). Large increases in the carbonate content and magnetic susceptibility of the sediments in Zone 1 (Figure 5) support the interpretation of an immediately post-glacial environment characterized by an unstable and rapidly changing landscape, as melting glacier ice would result in increased runoff and erosion of the surrounding watershed. For example, analysis of a lake sediment core from Prince of Wales Island (Gajewski and Frappier 2001) found low levels of organic matter, and high carbonate content in the basal portion of the record dated to about 6500 yr BP; these were interpreted as reflecting an unstable landscape associated with immediately post-glacial conditions.
The dominant local and regional taxa present in the earliest portion of the record from Lake SP02 include *Salix, Artemisia*, and Cyperaceae, with lesser abundances of Arctic herbs such as Ericaceae, *Oxyria*, and *Potentilla* (Figure 6). These taxa are characteristic of Polar Desert vegetation, and can be described as “herb tundra” (Bliss and Matveyeva 1992), which are commonly observed as pioneer vegetation for middle and high-Arctic sites (Gajewski 2000; Hyvarinen 1985). The fact that the percentages of *Salix* and *Artemisia* during this period are the highest observed for the entire record, suggest that these taxa responded more rapidly to improving environmental conditions following deglaciation of Melville Peninsula. Pollen analysis of a sediment core from Lake JR01 on Boothia Peninsula (Zabenskie and Gajewski 2007) also reported initial dominance of local and regional herbs like *Salix, Artemisia*, and *Oxyria*.

The relatively high percentages of long distance *Alnus* and *Betula* pollen percentages in the earliest section of the record, suggest that the productivity of local and regional vegetation, in terms of density on the landscape and volume of pollen produced, remained limited during this period (Figure 6). This idea is supported by the relatively higher long distance pollen accumulations observed for this period compared to those of the local/regional pollen component. However, the decreasing trend in the long distance pollen accumulation during Zone 1, combined with a simultaneous increase in the total pollen concentration from about 2000 to over 10,000 grains/ml (Figure 5) supports interpretations of improved productivity, and possibly increased density, of vegetation associated with the study site. Other studies, such as the pollen analysis of a sediment core from Lake KR02 on Victoria Island (Peros and Gajewski 2008), have used changes in pollen concentrations and accumulations (“pollen influx”) to provide estimates of past pollen production, where relative increases in the influx of local and
regional pollen were interpreted as indicators of improved ecological productivity at the study site.

Changes in the local and regional vegetation are observed in Zone 2 (5900-5300 yr BP) (Figure 6) with the introduction of Poaceae, and a significant increase in the relative abundance of Cyperaceae. Simultaneous decreases in the abundances of *Artemisia*, *Salix*, and Ericaceae are also observed, while Arctic herbs, such *Dryas* and *Oxyria*, remain constant. The observed increase in Cyperaceae, at the expense of *Salix* and *Artemisia* that dominated Zone 1, is consistent with pollen diagrams from the majority of middle and high-Arctic sites, where Cyperaceae typically comprises more than 50% of the local/regional pollen component (Bliss and Matveyeva 1992). Taxa such as Cyperaceae and *Salix* typically dominate Arctic pollen diagrams not because these plants necessarily occur in greater densities on the landscape, but rather because they are significant producers of wind-borne pollen (anemophilous), whereas other common taxa, such as *Dryas*, *Oxyria*, *Papaver*, *Ranunculus*, and *Saxifraga*, are either entomophilous or amphiphilous (Bliss and Matveyeva 1992).

Synchronous increases in the local/regional pollen accumulation rates, and decreases in the long distance accumulations compared to the preceding period, offer further support for the interpretation of improved ecological productivity at the study site during Zone 2. Therefore, variations in the relative abundances and accumulation rates of local/regional pollen during this time are interpreted as the continued development of herb tundra consistent with Polar Desert vegetation characteristic of middle and high Arctic sites (Bliss and Matveyeva 1992).

There is also a significant increase in abundance of *Sphagnum* at about 5700 yr BP. *Sphagnum* does occur in middle Arctic vegetation communities (Porsild 1964), but the spores
produced by this taxon are capable of long distance dispersal, and therefore it was not included in the local and regional pollen component for the study site. Furthermore, it is unclear how to interpret relative variations in the abundance of this taxon, as increased percentages of *Sphagnum* could imply increased moisture availability at the study site (Charman 2002).

Pollen Zone 3 is the final stage representing the middle Holocene period (5300-3900 yr BP). During this period there is further evidence for continued increases in the productivity of vegetation at the study site and Melville Peninsula in general, with increases in the relative abundance of Cyperaceae to nearly 50%, as well increasing trends in the profiles of *Artemisia* and Ericaceae (Figure 6). Other pollen studies from the Arctic (e.g. Hyvarinen 1985) have interpreted the emergence of Ericaceae, as well as other Arctic herbs, as possible evidence for a reduction in the extent and duration of snowbeds in the area, as such conditions are more suitable for the growth herbaceous ground cover in low-lying areas of the landscape. One of the strongest lines of evidence for increases in plant productivity at this time, compared to the preceding periods on Melville Peninsula, is a continued increase in the local/regional pollen accumulation rates to over 230 grains/cm²/yr, with a simultaneous decrease in the long distance pollen accumulation rates (Figure 6). A large spike in the total pollen concentration at approximately 4500 yr BP (40.5 cm depth) cannot be interpreted as reflecting actual changes in the productivity of vegetation at the study site, because this large increase is represented by only one sample point, the absolute value of which (~50,000 grains/ml) may have been exaggerated by a volumetric measurement error, as the volume of sediment sub-sampled is influenced by the amount of moisture present in the sample.

To summarize, the pollen data for Lake SP02 indicate that during the middle Holocene herb tundra vegetation began to develop at the study site immediately following deglaciation of
Melville Peninsula around 6500 yr BP. Productivity of local and regional vegetation continued to improve throughout the early Holocene, as indicated by increasing abundances of middle Arctic taxa, increasing local/regional pollen accumulation rates, and relative decreases in the inputs of long distance pollen from areas south of the study site. The term “productivity”, in this case, refers to changes in the reproductive and physiological traits of vegetation, such as plant density, above-ground biomass, and the quantity of pollen produced by the plant, which often vary by species (Chapin and Shaver 1985). These factors are most likely to influence local and regional pollen accumulations (Delph et al. 1997), especially when the types of vegetation occurring at the study site remain constant through time (Peros and Gajewski 2008).

**Late Holocene (3900 yr BP to present)**

The late Holocene in comprised of Pollen Zones 4a, 4b, and 4c, and covers the period from 3900 yr BP to present. Overall, the percent abundances of local and regional taxa remain relatively constant during this time period, with two important exceptions (Figure 6). The first exception occurs in Zone 4b, where a large increase in long distance *Pinus* pollen, as well as a much smaller increase in *Picea* pollen, are met with simultaneous decreases in Cyperaceae, *Salix*, and *Oxyria*. Also, total pollen concentrations and accumulations increase at the onset of the period, although they also decrease to the lowest levels in the record by the end of Zone 4b. There does appear to be a clear shift in the relative proportions of some of the dominant taxa between 1300 to 1000 yr BP, however, interpretations of the vegetation response at the landscape scale during this relatively brief period are difficult.

The second exception to the relative stability observed in the pollen profiles during the late Holocene occurs in the record between 1000 yr BP and present day (Figure 6), where
Ericaceae, *Salix*, *Betula* and *Sphagnum* show significant increases during the past 500 years, at the expense of declining abundances of *Pinus*, *Alnus*, and Cyperaceae. The apparent increase in the productivity of some Arctic plants in the uppermost sediments is supported by sharp increases in total and local/regional pollen accumulations during this same period, and may therefore represent a response to climate variability associated with the past millennium. Impacts on terrestrial vegetation during this time have been reported from other middle Arctic sites in Canada (e.g. Zabenskie and Gajewski 2007). Furthermore, the relative decline in Cyperaceae in the surface sediments of the core may not necessarily imply a reduction in the influx of pollen from this taxon, but instead could suggest relative increases in the productivity of other Arctic taxa such as *Salix*. Pollen percentages from long distance taxa show either slight increases, or remain stable for the most recent period in the record.

Determining the origins of long distance pollen represented in the SP02 record is important to understanding the relationship between these taxa and the productivity of vegetation at the study site. The fossil *Betula* profile likely consists of pollen from shrubs, *B. glandulosa* and *B. Nana*, which are common in low Arctic tundra (Gajewski 2002). *Alnus*, on the other hand, probably originated from the forest-tundra shrub *A. crispa*, which is common along the northern margins of continental Canadian Arctic (Porsild 1964). Pollen from *Pinus* and *Picea* originate in the boreal forest to the south of the study site. Differences in the pollen profiles of long distance taxa, such as *Pinus* and *Alnus*, may reflect differences in the migration history of each plant (Gajewski 2002). However, to confirm this, calculations of individual influxes for each taxon are required to establish if changing abundances reflect changing influxes. Another possibility is that individual long distance taxa are responding differently to environmental factors due to the proximity of the pollen source to Lake SP02. For example, much of the *Alnus*
pollen comes from a location much closer than *Pinus*. Therefore, the vegetation associated with the source area of *Alnus* pollen may have responded to the same environmental factors as the local and regional taxa.

*Alnus* shows a decreasing profile over the course of the entire record from 6300 yr BP to present (Figure 6). This decline may be due to relative increases in the local/regional pollen component, as reflected in the generally increasing profiles of total pollen concentrations. However, over shorter time scales, *Alnus* does increase in abundance in accordance with simultaneous increases in local and regional taxa (such as Cyperaceae at 61.0-62.5 cm depth), as well as in accordance with increasing local/regional pollen accumulations, as is the case for the uppermost sections of the record. Supporting the short-term response of *Alnus* to local and regional environmental conditions, are indications of increased ecological productivity during the time periods represented by Zones 1 and 2 based other proxies, including LOI$_{550}$, diatom concentrations, and BSi, all of which show increasing profiles during these periods (Figure 5).

In summary, pollen analyses of a sediment core from Lake SP02 reveals the persistence of Arctic herb tundra typical of Polar Desert regions throughout the middle and late Holocene record. The type of vegetation assemblage at the study does not appear to change in response to fluctuating environmental conditions since deglaciation of the Peninsula around 6500 yr BP. Rather, changing environmental and ecological conditions are more apparent from the relative changes in the percent abundances of dominant taxa, as well as from variations in the local and regional pollen concentrations and accumulations. This form of directional non-replacement succession is characteristic of most middle and high Arctic sites (Ritchie 1995), and is mainly due to limitations in the reproductive dispersal of many entomophilous Arctic taxa, as well as environmental limitations related to low temperature, nutrient deficiency, and limited soil
moisture (Bliss and Matveyeva 1992). Adding to this are problems related to the spatial scale of the pollen record and the inadequate level of taxonomic discrimination in pollen identification, as groups like Cyperaceae, Poaceae, and Artemisia are diverse (Kapp 2000). Therefore, future pollen studies from the Canadian Arctic should strive to improve the taxonomic resolution of the resulting diagram, and should carefully analyze variations in the accumulations of pollen from individual taxa, in an effort to better understand the relationships between fossil pollen assemblages, and Arctic vegetation dynamics.

6.2 Holocene paleoclimate variability on Melville Peninsula

*Holocene Thermal Maximum (HTM)*

The pollen record from SP02 shows evidence for long-term, low-frequency climate variations, including the HTM, which has been reported from sites across the Canadian Arctic (Kaufman et al. 2004). The main evidence in the pollen record from Lake SP02 for a period of optimal warmth suggests the HTM may have occurred between 5300 to 3900 yr BP (pollen Zone 3), and is based on changes in the relative abundances of dominant taxa such as Cyperaceae, relative increases in pollen concentrations and accumulation rates (Figure 6), as well as increasing trends in sediment organic matter, diatom concentrations, and BSi (Figure 5). The interpretation of the HTM during this period is further supported by observed decreases in the abundances of Arctic herbs such as Artemisia, and Dryas, which are taxa more tolerant of colder and drier environments (Gajewski 2002).

Other pollen studies from the Canadian Arctic have inferred the HTM from changes in the relative abundances of local and regional taxa (Gajewski 2000; Hyvarinen 1985; Zabenskie 69
and Gajewski 2007). For example, pollen analysis of a sediment core from Prince of Wales Island (Gajewski and Frappier 2001) interpreted increased pollen concentrations, mainly due to increased abundances of Cyperaceae, and simultaneous decreases in the abundances of high-Arctic taxa such as Poaceae and *Papaver*, as evidence for a period of optimum warmth between 6500 to 4000 yr BP. Such studies support the identification of the HTM in the SP02 pollen record.

This timing of the HTM for the study site between 5300 to 3900 yr BP is generally consistent with estimates of the timing of optimal Holocene warmth from sites to the west of Melville Peninsula. For example, reconstructions of mean July temperature from Lake JR01 on Boothia Peninsula using the modern analogue technique (Zabenskie and Gajewski 2007) suggest that peak Holocene temperatures were realized in the area between 5800 to 2800 yr BP. On the other hand, sites from Baffin Island located to the east of the study site (Andrews et al. 1979), report peak Holocene warmth between 3000 to 2500 yr BP. Therefore, middle Holocene climate changes at the millennial-scale for the study site appear to be more similar to sites to the immediate west. These results suggest that the nature of the climate for Melville Peninsula during the middle Holocene was analogous to the more continental climates associated with climate region IIa (Figure 1).

**Neoglacial cooling**

Following the HTM the pollen record from Lake SP02 shows evidence of gradually cooling temperatures that are consistent with a period of Neoglacial cooling. A prolonged period of progressively cooler temperatures following the HTM has been inferred from other studies based on shifts in the local and regional pollen taxa, and decreasing pollen concentrations.
(Gajewski et al. 2000; Gajewski and Frappier 2001; Hyvarinen 1985). The main evidence for Neoglacial cooling in the SP02 pollen record is found in pollen Zone 4a (3900 to 1300 yr BP) (Figure 6), with decreases in the abundances of taxa more typical of low and middle Arctic site, such as Salix, slight increases in high Arctic taxa like Oxyria and S. oppositifolia, and a generally decreasing trend in the profile of local and regional pollen accumulations. Relative decreases in other proxies, such as sediment organic matter, diatom concentrations, and BSi from Lake SP02 (Adams and Finkelstein 2010), support the interpretation of cooling conditions between 3900 to 1300 yr BP (Figure 5).

It is interesting to compare the estimated timings of millennial-scale climate variability for the study site as reconstructed using multiple proxies from sediment core SP02-H4. For example, increased diatom concentrations and %BSi (Figure 5) suggest that Neoglacial cooling may have commenced after 2900 yr BP (Adams and Finkelstein 2010), which is approximately 1000 years later than inferences based on the pollen stratigraphies from the same core. This discrepancy may reflect different timings in the responses of terrestrial and aquatic ecosystems to long-term environmental changes, with terrestrial vegetation showing a more rapid response to decreasing temperatures in this case. Furthermore, the observed agreement between the diatom data and the LOI550 profile for Lake SP02 (Figure 5) suggests that the majority of the organic matter in the sediments of the Lake was autochthonous in origin. Such distinctions are important when inferring paleoclimate variability from multiple proxies, as the source of the material can influence the direction and timing of the signal. For example, fluctuations in the sediment organic matter of an autochthonous source may be influenced more by limnological factors, such as pH and nutrient availability, as opposed to regional-scale climate changes (Fritz 2008).
Medieval Warm Period (MWP)

The pollen record from Lake SP02 also contains evidence for short-term, high-frequency climate changes that occur at sub-millennial and centennial timescales. Unlike climate variability at the millennial-scale, however, short-term climate changes are often not as apparent in the fossil pollen assemblages of local and regional taxa (Peros and Gajewski 2008). The main evidence for short-term climate shifts in the SP02 pollen record, which have been interpreted as possible evidence for the MWP, corresponds to pollen Zone 4b, and covers the period 1300 to 1000 yr BP (Figure 6). During this period there are increases in the relative abundances of long distance pollen representing *Pinus* and *Picea*, which may indicate increased prevalence of warmer air currents from areas to the south of the study site (Zabenskie and Gajewski 2007; Bourgeois et al. 2000). Such conditions would not only result in warmer temperatures on Melville Peninsula through the introduction of warmer air masses, but could also result in more efficient transport and delivery of long distance pollen from forests to the south of the study site.

Supporting interpretations of the MWP in the SP02 pollen record are the observed increases in total pollen concentrations and accumulation rates at 1300 yr BP (Figure 6), in addition to the LOI$_{550}$, diatom concentration, and BSi profiles (Figure 5), all of which show relative increases at approximately 1000 yr BP. The most convincing evidence for the MWP comes from the % BSi profile, which shows values for this period that are the highest since the mid-Holocene (HTM). Several studies from the Canadian Arctic have provided evidence for potentially warmer temperatures between 1300 to 1000 yr BP (Finkelstein and Gajewski 2007; Mober et al. 2005). For example, Podritske and Gajewski (2007) report similar increases in diatom concentrations, species richness, and organic matter in lake sediments from western Victoria Island during the earliest part of the past millennium.
Identification of short-term climate changes associated with the past millennium from the SP02 pollen data suggest that the timing of the MWP for Melville Peninsula is more similar to sites to the east, in climate region IVb (Figure 1). For example, a high-resolution record from Baffin Island (Moore et al. 2001) indicates the presence of warmer temperatures between 900-1300 yr BP. Results from JR01 on Boothia Peninsula, on the other hand, indicate cooling temperatures between 1300 to 1200 yr BP. Therefore, the climate regime associated with Melville Peninsula during the late Holocene, may be more similar to the maritime influenced climates to the east of the study site in region IV (Maxwell 1980).

These results indicate a potential shift in the climate boundary that currently resides over Melville Peninsula (region IIb), with climates of the middle Holocene similar to those of the continental Canadian Arctic, and climates during the late Holocene exhibiting a more maritime influence. This westward shift in the boundary between these two climate regions over the course of the last millennium may be related to changes in isostatic depression and sea-ice cover (Adams and Finkelstein 2010). However, evidence for enhanced coastal erosion of the shoreline on Melville Peninsula indicates that there may have been less sea-ice during the middle Holocene (Dredge 1995), and ice-free conditions in the Foxe Basin during this time would have likely increased the maritime influence on the climate of Melville Peninsula (Adams and Finkelstein 2010; Dyke and Morris 1990). As a result, one would expect the position of the boundary with respect to the study site to shift eastward, with climates during the late Holocene on Melville Peninsula more similar to sites to the west.

A diatom analysis of Lake SP02 (Adams and Finkelstein 2010), confirms this expectation, with late Holocene climates for the study site more similar to those from Boothia Peninsula (Zabenskie and Gajewski 2007). However, the lack of information on paleoclimates
in the region, especially with respect to areas west of the study site where there are no available ice core records, make such inferences tentative at best. Therefore, more multi-proxy, high-resolution, paleoenvironmental records from the region are required before such issues can be resolved.

*The Anthropocene*

There may also be evidence for recent climate changes in the uppermost section of the pollen record from SP02. The past 150 years in the SP02 record is represented by the top 4.5 cm of the core, during which time there are observed increases in the relative abundances of Ericaceae, *Salix*, and *Betula*. While total pollen concentrations during this time do not show a significant increase, all of the pollen accumulation profiles show large spikes in the past 100 years of the record (Figure 6). There are also increases in the sediment organic matter content (LOI$_{550}$) and %BSi in the uppermost sections of the record (Figure 5), which support the interpretation of a recent warming signal. Furthermore, one would expect relative increases in the abundances of shrubs such as *Salix* and *Betula* under warmer conditions, as there is evidence to suggest that these taxa have been migrating northward across the sub-Arctic in accordance with recent warming (Tape et al. 2006).

Unfortunately, the pollen diagram from Lake SP02 includes only 2 samples corresponding to the 20$^{th}$ century. Furthermore, since the surface sample from SP02 did not yield an adequate concentration of pollen for a sufficient pollen sum, any inferences of 20$^{th}$ century environmental change are based on only a single sample from about 2.5 cm depth (~1940 AD). Therefore, despite significant indicators of an ecological response to recent warming in the SP02 pollen record, increased temporal resolution and higher total pollen sums
for the uppermost sediments are required in order to make any meaningful inferences on the potential impacts of 20th century climate change.

**Summary of paleoclimate variability on Melville Peninsula**

The pollen record from Lake SP02 suggests that variations in the relative abundances of dominant taxa, and pollen concentrations may be controlled by climate over millennial time scales. During periods when pollen abundances remain relatively constant, pollen concentrations are likely influenced by changes in regional plant productivity (Peros and Gajewski 2008), including the density of vegetation on the landscape, and the quantity of pollen produced (Delph et al. 1997). However, these adaptations are in turn controlled by environmental variables, such as climate. Therefore, pollen percentages in the record from SP02 show more gradual changes through the Holocene, such as the HTM, as inferred from increased pollen concentrations, increased abundances of pollen from taxa more typical of low and middle Arctic sites like Cyperaceae, and simultaneous decreases in those taxa more common at high Arctic sites such as *Dryas* (Figure 6).

Fluctuations in pollen accumulation rates, on the other hand, may be due to changes in individual plant structure, density, and productivity at the landscape scale, and therefore have the potential to document vegetation responses to centennial to millennial-scale climate changes. For example, a pollen diagram produced for Lake KR02 on Victoria Island (Peros and Gajewski 2008) shows very little change in local and regional taxa such as *Artemisia* and *Salix*, while pollen influx values of various herbs fluctuated at sub-millennial time scales in accordance with the GISP2 ice-core record of mean annual temperature spanning the past 10,000 years (Alley 2004). This was also the case with Lake SP02, where changes in long-distance pollen
accumulations, as well as variations in the organic matter content and %BSi have been interpreted as possible evidence for the MWP, and in the absence of any major changes in the fossil pollen assemblages of local and regional taxa at the study site. There is also potential evidence for a recent warming signal in the uppermost sections of the record, but an inadequate sample size precludes any conclusions with respect to the 20\textsuperscript{th} century.

Comparisons of the timing of Holocene climate changes at multiple time-scales for the study site with regions adjacent to Melville Peninsula suggest a potential westward shift in the boundary between major climate zones. Millennial scale climate changes during the middle Holocene, like the HTM, were more similar in timing and rate when compared to sites to the west of the Peninsula. Climate shifts at shorter time-scales, such as the MWP, during the late Holocene for the study site are in better agreement with reconstructions from sites to the east of the Peninsula. These results contradict what one would expect based on the influence of relatively less sea ice in the Foxe Basin during the middle Holocene. Currently, more paleoenvironmental studies are required to resolve these questions, especially in areas to the west of Melville Peninsula.
7 Conclusions

Studies documenting vegetation and paleoclimate variability in the Canadian Arctic are considered crucial for investigations of the nature and impacts of future climate change. A sediment core from Lake SP02, Melville Peninsula, Nunavut, was radiocarbon dated to ~6300 yr BP, and analyzed for fossil pollen, magnetic susceptibility, organic matter, and carbonate content. Key questions in this study are: How did terrestrial plant communities at the study site respond to post-glacial environmental variability? Does the high-resolution pollen record (~150-250 years per sample) from Lake SP02 offer evidence for millennial and sub-millennial paleoclimate changes during the Holocene? How do these results compare with study sites in adjacent climate regions, and with a previously published diatom record from the study site? And finally, what do these results suggest about the nature and causes of paleoclimate variability on Melville Peninsula?

Pollen abundances, concentrations, and accumulation rates indicate that herb tundra vegetation was present at the study site following deglaciation of the Peninsula (~6300 yr BP), and persisted throughout the remainder of the Holocene. Productivity of terrestrial vegetation at the study site, in terms of plant density, above-ground biomass, and quantity of pollen produced generally increases during the middle Holocene, and culminates in a period of optimal warmth between 5300 to 3900 yr BP, interpreted as evidence for the Holocene Thermal Maximum (HTM). Relative abundances of long distance and local/regional pollen, as well variations in pollen concentrations, pollen accumulations, sediment organic matter, and diatom concentrations suggest a prolonged period of Neoglacial cooling between 3900 to 1300 yr BP. A period of relative warmth was also identified at 1300 to 1000 yr BP, interpreted as evidence for the
Medieval Warm Period (MWP), followed by significant changes is local and regional pollen
abundances, and pollen accumulation rates associated with the 20th century, which are
interpreted as a response to recent climate change.

These results are supported by records from across the Canadian Arctic, which highlight
major patterns of Holocene climate change at multiple spatial and temporal scales. Comparisons
of the proposed timings of these climate events for Melville Peninsula with adjacent sites,
suggest a westward shift in the climate boundary separating continental and maritime climate
regions in the eastern Canadian Arctic. Furthermore, a lack of conformity between pollen and
diatom based paleoclimate inferences from Lake SP02 indicates a difference in the responses of
terrestrial and aquatic indicators of paleoenvironmental change. However, further studies are
required to better understand how Arctic ecosystems respond to environmental variability over
multiple spatial and temporal scales.

The general aim of the International Polar Year (IPY) initiative working out of the
Melville Peninsula is to integrate the results of paleoenvironmental research with archaeological
data in an effort to better understand the potential influences of Holocene climate changes on
prehistoric human migration and settlement patterns (Ross 2007). Therefore, the results of this
study may be used by others working on coupling cultural histories with paleoenvironmental
records in the Arctic.
References


Gajewski, K. 2002. Modern pollen assemblages in lake sediments from the Canadian Arctic. Arctic, Antarctic, and Alpine Research 34, 26-32.


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### Tables

<table>
<thead>
<tr>
<th>Depth of bottom edge of current section (cm)</th>
<th>Age at Bottom of Extrapolated Section in Years Before 2009 AD (CRS Model Estimate)</th>
<th>Po-210 Total Activity (DPM/g)</th>
<th>Po-210 Unsupported Activity (DPM/g)</th>
<th>CRS Sediment Accumulation Rate (g/cm²/yr)</th>
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**Table 1**: Total and unsupported $^{210}$Pb activity for sediment core SP02-H4, including sediment accumulation rates, and age estimates (years BP) based on the constant rate of supply (CRS) model.
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**Table 2:** Total and unsupported $^{210}$Pb activity for sediment core SP02-H2-G2, including sediment accumulation rates, and age estimates (years BP) based on the constant rate of supply (CRS) model.
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**Table 3:** Radiocarbon dates and calibrated ages from sediment core SP02-H4. “Organics” refers to both plant remains and chitinous remains (mostly chironomid head capsules) picked by hand on a stereomicroscope. * Sample not included in the age-depth model
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Table 4: Total species richness (Max S.R.) of pollen taxa for each level, and the number of palynomorphs observed (Number of observations) at the time that maximum species richness values were reached. The surface sample (0.5 cm) was excluded from calculations of descriptive statistics due to an inadequate pollen sum.
Figure 1 – Map of Maxwell’s (1980) climate regions for the eastern Canadian Arctic. Melville Peninsula is situated in a transitional climate zone (IIb), between the colder, continental climates to the west (IIa), and the relatively warmer, maritime climates to the east (IVb). The location of Hall Beach, which is the nearest community to the study site, is indicated on the Melville Peninsula. Also shown are other sites mentioned in the text. Cartography courtesy of Julie Ross and Steve Perry.
Figure 2: Aerial photograph of the Sarcpa Lake region, Melville Peninsula, Nunavut. Lake SP02 used for pollen analysis is indicated, in addition to the much larger Sarcpa Lake. Image was acquired July 28, 1957. Courtesy of National Air Photo Library.
Figure 3: Radioisotope $^{210}\text{Pb}$ decay series of total activity (decays per minute (DPM)/g) of each sample vs. depth in the core (cm) for the uppermost samples from core SP02-H4 (solid line), and core SP02-H2-G2 (dashed line), based on $^{210}\text{Pb}$ analysis performed by Flett Research Ltd.
Figure 4: Chronology for core SP02-H4 based on $^{210}$Pb dates from the uppermost 3.5 cm and five AMS radiocarbon dates. Linear interpolation was applied between the median value of each 2-sigma calibrated radiocarbon date range and the lowermost $^{210}$Pb date to produce the age model. One radiocarbon date from 55.5-58.5 cm depth (8840 yr BP) was rejected, and was therefore not included in the age model (Table 1).
Figure 5: Diagram for sediment core SP02-H4 showing (from left to right): % organic matter (LOI 550), % carbonate content (LOI 950), magnetic susceptibility (SI units), diatom concentrations (valves/g) and biogenic silica (%) (Adams and Finkelstein 2010), total pollen concentration (grains/ml), and sediment accumulation rate (mm/year). Zones are based on stratigraphically constrained, unweighted least squares cluster analysis of the local and regional pollen data. ‘*’ indicates one pollen concentration value at ~50,000 grains/ml.
Figure 6: Pollen diagram for Lake SP02 from 6300 yr BP to present (71-0 cm), including all long distance, local and regional, as well as spore taxa. Also shown are the total pollen concentrations (grains/ml), as well as the total, long distance, and local/regional pollen accumulation rates (grains/cm²/yr). Pollen abundances are expressed as percentages of the total pollen sum. Zones are based on stratigraphically constrained, unweighted least squares cluster analysis of the local and regional pollen data. ‘*’ indicates one pollen concentration value at ~50,000 grains/ml.
Appendices

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Appendix A: Raw pollen counts for Lake SP02, between 0-71cm sediment depth (n=29)
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**Appendix A:** Raw pollen counts for Lake SP02, between 0-71cm sediment depth (n=29)
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Appendix A: Raw pollen counts for Lake SP02, between 0-71cm sediment depth (n=29)
Results of SPLITLSQ

Unweighted least squares analysis

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**Appendix B**: ZONE output using the SPLITLSQ algorithm, based on unweighted least squares cluster analysis of local and regional pollen counts (expressed as percentages).