Paleoenvironmental Reconstruction of the Pliocene Aged Beaver Pond Site (Ellesmere
Island, NU)

by

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Abstract:

The Pliocene aged Beaver Pond site, found in Canada's High Arctic (Ellesmere Island, NU), has produced a rich fossil vertebrate fauna. The site is composed of a thick sequence of peat and sand. Neogene terrestrial deposits with peat accumulations are common occurrences in the Arctic, but this site is unique due to the thickness of the peat, associated vertebrate fossils and a number of beaver cut sticks. Although the site has been the subject of intense paleontological investigations for almost two decades, there has not been a detailed reconstruction of the depositional history of the site. Measured sections within and surrounding the site established the stratigraphy and lateral continuity of the stratigraphic units. Grain size analysis, loss on ignition, and diatom contents were examined to determine environmental changes. Facies changes as indicated by sedimentological characteristics (i.e. grain size, organic content) suggest an initial floodplain system that deposited rip-up peats. This environment changed to a rich fen that supported peat accumulations up to 240 centimetres thick and was associated with a deeper still-water environment evidenced by new fossil diatom findings and previously discovered vertebrate findings. Whereas peat extends widely along the outcrop, this increased thickness is localized to a small portion of the fossil site. Abundant beaver-cut sticks and specimens of the fossil beaver *Dipoides* sp. are associated with the peat layer, a characteristic after which the site was named. *Dipoides* sp. may have been a keystone species in the wetland and possibly attracted wildlife to the area through ecosystem engineering (i.e. possible dam building, tree harvesting etc.). The peat is overlain by fine-grained sand rich in organic matter and charcoal, which is suggestive of forest fires and may have been related to the end of paludification in the area. Alignment of twigs

suggests flow was re-established in a small creek or stream. The maximum known thickness of the peat deposit suggests the peatland growth lasted for approximately $49,000 \pm 12,000$ years, which indicates climate stability during the existence of this site during the Pliocene.

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Introduction

The geologic record of the Canadian High Arctic reflects past climatic phases that supported vastly different ecosystems in contrast to the barren landscape found in the Arctic today. The Pliocene aged Beaver Pond site, located at Strathcona Fiord on West-Central Ellesmere Island (Nunavut, Canada), preserves a large fossil rich peat accumulation (Figure 1). This site was discovered in 1961 by Dr. John Fyles of the Geological Survey of Canada and has been the subject of intense paleontological and paleoclimatic investigation since the early 1990's (Hulbert & Harington, 1999; Hutchison & Harington, 2002; Elias and Matthews, 2002; Tedford & Harington, 2003; Ballantyne et al., 2006; Murray et al., 2009; Ballantyne et al., 2010; Csank et al., 2011a-b). This locality is significant because it is to this date the only Pliocene aged site in the North American High Arctic to yield a significant amount of vertebrate fossils. Of particular interest is the evidence for what has been reported as possible remains of a fossilized beaver dam including many beaver cut sticks and an abundance of the fossil beaver *Dipoides* sp. (Tedford and Harington, 2003; Rybczynski 2008). Over the past two decades, most research on the site has focused on excavation and fossil recovery with little emphasis put on stratigraphy and sedimentology. Paleoenvironmental interpretations were based on fossil assemblages. A diverse fossil mammal assemblage has been recovered from the Beaver Pond site, which includes numerous species whose living relatives occupy woodlands (Tedford & Harington, 2003). The plant community recovered from the site is a mix of larch-dominated forest elements and plants such as dwarf birch, commonly found in mineral-rich wetlands (i.e. groundwater fed fens). Many

of the fossil mosses found in the area are indicative of floodplain environments (Matthews & Ovenden, 1990; Ovenden, 1993).

Figure 1: Map showing the Beaver Pond fossil site on Ellesmere Island, Nunavut. The star marks the location of the fossil site ($78^{\circ}31'N$, $82^{\circ}22'W$). Note: Projection of insert differs from main map.

The objectives of this study are to describe the stratigraphy and sedimentology found at the Beaver Pond site, relate this information to Pliocene paleoenvironmental change, calculate duration of the peats at the Beaver Pond site, and describe how beaver activity may be related to the Beaver Pond site.

Since the Eocene thermal maximum (~55 million years ago) Earth's climate has generally been cooling (Zachos et al., 2001). Although the climate during the Pliocene was variable, a cooling trend occurred, except during the Mid-Pliocene Warm Period (2.9–3.3 Ma) (Raymo et al., 2011). A number of publications have used a variety of proxies to reconstruct past temperatures during deposition of the Beaver Pond site (Table

1). The Beaver Pond site, dated to 3.4 ± 0.3 Ma was deposited before the onset of the last major glaciations of the northern hemisphere (Rybczynski, 2012). The mid-Pliocene warm phase is an important analogue because it represents the last time the Earth was significantly warmer than present with the same continental arrangement, and therefore can be used as a model for future warming (Jansen et al., 2007). The average winter

Table 1: Summary of mean annual temperature and growing season temperature* reconstructions for the Beaver Pond site.

Temperature difference	Method	Author
10–15°C*	Biological association	Elias and Matthews (2002)
14.2°C	$\delta^{18}\text{O}$ /ring width: Fossil Larch	Ballantyne et al. (2006)
19.1°C	tetraether lipids	Ballantyne et al. (2010)
19.2°C	$\delta^{18}\text{O}$: Fossil Larch	Ballantyne et al. (2010)
19.3°C	Paleovegetation	Ballantyne et al. (2010)
18.3°C	$\delta^{18}\text{O}$ /ring width: Fossil Larch	Csank et. al. (2011a)
11–16°C*	$\delta^{18}\text{O}$: Fossil Larch & aragonitic molluscs	Csank et. al. (2011b)

temperature is -41°C at Ellesmere Island today while the average summer temperature is 2.4°C . A diverse beetle assemblage recovered from the site, most of which are extant taxa, was used to infer winter temperatures that were 15°C warmer than present (-26°C) and summer temperatures that were 10°C warmer than present (12.4°C) (Elias and Matthews, 2002). A study that compared larch tree ring widths combined with $\delta^{18}\text{O}$ isotopes from an extinct fossil larch (*Larix groenlandii*) recovered from the Beaver Pond site to modern larch (*Larix laricina*) collected further south, found that the mean annual temperature in the High Arctic during the Pliocene was -5.5°C , 14.2°C warmer than today (Ballantyne et al., 2006). Ballantyne et al., (2010) improved on the methods used in the previously described study and added two additional independent proxies. The research used fossil tetraether lipids from soil bacteria, oxygen isotope ratios ($\delta^{18}\text{O}$) and

annual tree ring width in fossil wood combined with the composition of paleovegetation to estimate temperature. The $\delta^{18}\text{O}$ analysis in their study used material from fossil mosses to improve the temperature estimate. These approaches produced a mean annual temperature of -0.6°C , -0.5°C , and -0.4°C respectively. This is a difference in mean annual temperature of 19.3°C compared to today (Ballantyne et al., 2010). Other estimates using *Larix* sp. tree ring widths and stable oxygen isotopes measured a mean annual temperature of $-1.4 \pm 4.0^{\circ}\text{C}$, which is $18.3 \pm 4.1^{\circ}\text{C}$ warmer than present (Csank et al., 2011a). Compared to previous studies, the tree ring analysis was expanded by incorporating one tree from the Beaver Pond site as well as three more fossil tree samples from nearby locations, which have been inferred to exist at the same time as the Beaver Pond site. Another recent paleotemperature reconstruction at the Beaver Pond site used $\delta^{18}\text{O}$ values from peat to determine meteoric water content ($-20.7 \pm 0.3\text{‰}$) and combine that with $\delta^{18}\text{O}$ values from aragonitic freshwater mollusks collected within the peat to estimate the temperature found at the Beaver Pond site during the Pliocene. This was the first thermodynamic proxy used to evaluate temperature at the site and found that at the time of deposition, the summer temperature was $11\text{--}16^{\circ}\text{C}$ warmer than it is today (Csank et al., 2011b).

As is evident from these studies, the High Arctic climate was much warmer during the Pliocene (Table 1), but CO_2 levels were similar to today (Pagani, et al., 2010). Current climate models predict a $10\text{--}15^{\circ}\text{C}$ increase in temperatures throughout the Arctic but results from the Beaver Pond site suggest that warming may be even greater (Haywood et al, 2009; Table 1). Due to this, determination of ecological conditions

during the formation of the Beaver Pond site is an integral step to add context to the existing body of science relevant to the site.

Geological Setting

The Beaufort Formation is a widespread, easily recognized stratigraphic unit in the High Arctic, composed mainly of a thick layer of Pliocene aged sands and gravels. Fossilized plant material, typical of a forest environment, is a common component of the Beaufort Formation. The type section, interpreted as braided river deposits, is located on Prince Patrick Island in the western Arctic (Fyles, 1990). Early studies suggested that the Beaufort Formation extended south to Banks Island and as far north as Meighen Island, but was later revised to limit its range to the western Arctic and excludes possible time-equivalent deposits on Ellesmere Island and elsewhere (Fyles, 1990).

On Ellesmere Island, “high terrace” sediments form an equivalent to the Beaufort Formation. This nomenclature will be used until the “high terrace” sediments found at Strathcona Fiord are formally named. These sediments, deposited during the Pliocene, overlie the Paleogene aged Eureka Sound Group (Figure 2). The Beaver Pond site is situated in these “high terrace” sediments at the head of Strathcona Fiord at an elevation of 380 metres. The regional stratigraphy described above is based on Marincovich & Zinsmeister (1991), who examined Tertiary marine mollusks found in the Eureka Sound Group at Strathcona Fiord.

Figure 2: At Strathcona Fiord an unconformity represented by the black line separates the Pliocene aged “high terrace” alluvium equivalent to the Beaufort Formation and the Mount Moore Formation of the Eureka Sound Group. The Margaret Formation is not present at the Beaver Pond locality (Stratigraphy adapted from Marincovich & Zinsmeister, 1991).

No detailed stratigraphy has been completed at the Beaver Pond site since its discovery and subsequent paleontological excavation. Matthews & Ovenden (1990) speculated that the site may be slumped, however, our recent field observations contradict this interpretation.

The Beaver Pond site is composed of fossil-bearing peat bound by two thick sand bearing layers. No depositional hiatus can be observed within the peat (Tedford & Harington, 2003). The peat contains beaver cut sticks as well as a number of vertebrate fossils, all of which are exquisitely preserved. The state of preservation can be attributed to the compressibility of peat. Some authors have suggested that the fossilized peat deposits at the site represent a beaver made pond (Hutchison & Harington, 2002; Tedford & Harington, 2003; Dawson & Harington, 2007; Murray et al. 2009). The flora and fauna recovered from the site indicate a “boreal forest” type environment. Before excavation

began in 1992, the peat was 240-centimetres thick, but following excavations it has been reduced to a thickness of approximately 100 centimetres (Figure 3).

Biostratigraphy and Geochronology

As previously mentioned, the Beaver Pond site forms an equivalent to parts of the Beaufort Formation as found on Meighen Island, which has been reliably dated to approximately 3.3 Ma (Matthews & Telka, 1997). It was speculated that the Beaver Pond site was older than the Meighen Island deposits but younger than the Late Miocene (3.5–5 Ma) (Matthews & Telka, 1997). Other previous attempts to date the site were performed by biostratigraphic correlations of vertebrate fossil assemblages recovered from the Beaver Pond site. Comparison to similar mammalian fossil assemblages found in southern localities such as Hagerman, Idaho and White Bluff, Washington, suggested an Early Pliocene age of 3.5–4.3 Ma (Hulbert & Harington, 1999). Tedford & Harington (2003) later revised the age to 4–5 Million years, based on the presence of numerous Eurasian taxa that compare well to Pliocene vertebrate fossils recovered from the Yushe Basin in China. The most recent date is based on cosmogenic nuclide dating of coarse-grained sand collected immediately above the thickest peats of the Beaver Pond site. This method used isotopic ratios of aluminum and beryllium to determine that the sand was 3.4 ± 0.3 Million years old (Rybczynski et al., 2012).

Figure 3: Left – The Beaver Pond site before major excavations began. The peat block is 240 cm thick (Photo: Kennedy/CMN). Right – The Beaver Pond site in 2010. Notice the peat block has been excavated (Photo: M. Lipman).

Paleobiological Communities and Paleobiogeography of the Beaver Pond Site

Well preserved Neogene vertebrate remains are uncommon at high latitudes (Elias & Matthews, 2002). The Beaver Pond site is the only Pliocene aged fossil site in the North American Arctic to yield any significant amount of vertebrate remains. The site is named after a fossil commonly recovered from the site, a small beaver, *Dipoides* sp., as well as the presence of a number of well-preserved beaver cut sticks found at the site. The species richness of fossils recovered at the site is unusually high, even amongst invertebrate remains, which are fairly common in Beaufort Formation deposits (Matthews & Telka, 1997). The rich mammalian fossil assemblage includes: a shrew, *Arctisorex polaris*, (Hutchison & Harington, 2002), a rabbit (*Hypolagus* sp.), a primitive ursine bear: *Ursus abstrusus*, a small canine, *Eucyon* sp., three mustelids including a large wolverine (*Plesiogulo* sp.), a fisher (*Martes* sp.) and a badger (*Arctomeles sotnikovae*) (Tedford & Harington, 2003), a tridactyl: *Plesiohipparion* sp. (Hulbert & Harington, 1999) and an artiodactyl: *Boreameryx braskerudi* (Dawson & Harington, 2007). Some non-mammalian fossils recovered from the site include a frog, a duck, and a fish: *Sander teneri* (Hulbert & Harington, 1999; Murray et al., 2009). The plant community includes ten bryophytes and 34 vascular plant taxa (Hulbert & Harington, 1999). *Scorpidium scorpioides* dominates the bryophyte component of the peat deposits and represents a taxon commonly found in mineral-rich fens (Matthews & Ovenden, 1990). The assemblage of vascular plants is dominated by wetland species but also includes larch cones and needles. This suggests the wetland was surrounded by an open larch forest (Matthews & Ovenden, 1990).

Until the latest Miocene (5.4–5.5 MY) the Bering land bridge was an important route of intercontinental migration between North America and Eurasia (Gladenkov et al., 2002). The fossils recovered from the Beaver Pond site show a mix of North American and Eurasian affinities, but are dominated by Eurasian taxa. Amongst vertebrates, only three specimens found at the Beaver Pond site have long histories in North America (*Dipoides* sp., *Hypolagus* sp., and *Eucyon* sp.) before dispersing to Europe (Tedford & Harington, 2003). At nearby fossil sites, remains of a Japanese stone pine (*Pinus pumila*) have been recovered. This taxon is an Asian species common to alpine areas and reaches tree line at the northern extent of its range today (Matthews & Oviden, 1990). Also, the Asian oribatid mite *Proteremaeus macleani*, commonly associated with *P. pumila* has been recovered from the Beaver Pond site (Matthews & Telka, 1997).

Methods

Field Methods

Fieldwork was conducted at the Beaver Pond Site for seven days during the summer of 2010. Six stratigraphic sections, designated as sections A through F, were measured in order to determine the lateral continuity of beds and to determine if the site of interest represents a slumped deposit (Figure 4). Heights of sections vary from 80 to 400+ centimetres and were strategically located to display variability of spatial characteristics of the site. Sections A through D were located within a ten-metre lateral interval and represent the main sampling area. Sections E and F were located approximately 40–50 metres southwest and northeast of the main sampling area. A total

of eighty samples were collected at irregular intervals in order to sample vertical changes in lithologies. Important boundary layers were documented and subsampled in order

Figure 4: Locations of stratigraphic sections recorded at the Beaver Pond site during the summer of 2010. The distance between Section A and Section C is approximately ten metres. Section A through D represent the main sample area and sections E and F were sampled to examine the lateral consistency of the beds.

to gain information about the paleoenvironmental history of the site. A count of beaver cut and non-beaver cut sticks was performed throughout the sampling area. Additionally, variation of different peat types was characterized in the field.

Laboratory methods

The 80 field samples were partitioned in the following way. Samples for grain size analysis and diatom examination were prepared together and treated to remove all organic material and carbonates. Another sub-sample set was used for Loss on Ignition.

Diatoms

Diatoms are photosynthetic algae (Class: Bacillariophyceae) that are sensitive indicators of changes in their environment. They can exist in colonies but are more commonly found solitarily. Diatoms have a cosmopolitan distribution and are found in almost all aquatic environments. They can be benthic, living in the substrate of a water body, or planktonic, living in the water column (Round, 1981). Due to their preference for particular environmental parameters (i.e. pH, temperature, nutrient dynamics etc.) many diatom taxa are useful paleoenvironmental indicators for examination of the fossil record. Marine diatoms have been documented as early as the Cretaceous, while earliest freshwater taxa have been found in Eocene aged strata (Bradbury, 1988). The siliceous cell walls of diatoms allow for relatively good preservation and easy identification in the fossil record. Diatoms are best preserved in cold, soft water (Ryves et al., 2006).

The samples (BPA01-BPF80) collected from the Beaver Pond site were sub-sampled to investigate their diatom contents. All samples were weighed, washed with 10% hydrochloric acid to remove carbonates then washed with a mixture of nitric and sulphuric acids (full concentrations) to remove organic material. The raw material was divided. One half was used to examine diatom content of the samples with a light microscope and scanning electron microscope (SEM), while the other half was used for grain size analysis. Only a small amount of processed material was mounted on glass

slides and on SEM stubs to be examined. On each slide/stub examined, five transects were performed. The diatom samples are housed at the Canadian Museum of Nature in the Canadian National Collection for Algae catalogued as CANA 85062–850142, 85159–85164, and 85167–85170.

Sedimentology and Loss on Ignition

Aquatic systems can be characterized by their sedimentary structures that might indicate flow patterns and grain size distribution that is the result of environmental energy conditions (lentic vs. lotic), while the grain shape and texture may indicate degree of transport.

For grain size analysis, the less than two millimetre grain size was used. Eighty sedimentological samples that had been treated to eliminate all carbonate and organic material were allowed to dry and then turned into a paste with a diluted Calgon solution in order to ensure sediment separation. This paste was then subjected to grain size analysis with a Beckman–Coulter LS 230 laser diffraction particle size analyzer. The software used to analyze the samples calculated various mathematical parameters (i.e. mean, mode, sorting, skewness, and kurtosis) using the Fraunhofer optical model.

Loss on ignition (LOI) is an efficient method to determine the organic matter and carbonate content of a sediment sample. When subjected to heat, organic material and carbonates can be quantifiably eliminated from a sediment sample. For each sample, approximately one cubic centimetre of material was weighed and placed in a ceramic crucible. Samples were dried at 110°C for 24 hours to eliminate any moisture. The samples were weighed again then placed in a Blue–MOV–18A muffle furnace at 550°C for four hours to eliminate organic material. The samples were weighed once more then

heated to 950°C for two hours in the muffle furnace to eliminate any carbonate material. The samples were weighed one final time after all organic material and carbonates were eliminated. The amount of organic material and carbonate material in the sample was then calculated using the following equations outlined by Heiri et al. (2001).

To determine the organic content:

$$\text{LOI}_{550} = 100 * ((\text{Dry weight}_{110} - \text{Dry weight}_{550}) / \text{Dry weight}_{110})$$

To determine carbonate content

$$\text{LOI}_{950} = 100 * ((\text{Dry weight}_{550} - \text{Dry weight}_{950}) / \text{Dry weight}_{110})$$

Peatland Duration

No estimates of the duration of the peatland that occupied the Beaver Pond site have been suggested, although such estimates would be useful for interpreting climatic stability and ecosystem transition during the Pliocene. This is especially important in areas that are sensitive to climatic changes such as the High Arctic. Tedford and Harington (2003) hypothesized that the deposit spans a long period of time and that there was no interruption in deposition. Duration of Holocene aged peats can be calibrated with carbon dates, but carbon dating methods cannot be used in this study due to the age of the site. To estimate the duration of the peatland at the Beaver Pond site, a literature search was performed to find the mass of peat added per square centimetre per year from modern rich fens in Finland and Alaska with mean annual temperatures that range from 0–1°C (Table 2). The volumes of four peat samples from the Beaver Pond site were calculated by 3D scanning the samples with an Arius 3D laser scanner at the Arius 3D imaging centre, Canadian Museum of Nature. Each sample was weighed to calculate the density of the Beaver Pond peats. Finally the organic content was calculated via LOI.

Table 2: Peat addition rates and geographic details pertaining to the five modern analogue sites used to estimate the duration of the peatland at the Beaver Pond site.

Analogue Site no.	Literature Source	Locality	Lat/Long	MAT	Peat addition rate (g Carbon/sq. cm/year)
1	Yu et al. (2009)	Alaska	60°27'/151°14'	0	0.00131
2	Yu et al. (2009)	Alaska	60°38'/151.04'	0	0.00123
3	Yu et al. (2009)	Alaska	60°25'/150.54'	0	0.00107
4	Mäkilä and Moisanen (2007)	Finland	68°24'/23°33'	0	0.00137
5	Mäkilä et al. (2001)	Finland	65°39'/27°19'	1	0.00224

Variables used to calculate the peat duration include: Peat thickness (100 cm; 240 cm), grams of carbon per cubic centimetre per year added to the peatland (Table 2), volume of a one-square centimetre column of fossil peat for each thickness (100 cm³; 240 cm³), average fossil peat density (weight/volume: 277g/ cm³), and the mass of the column of one-square centimetre for each height (100 cm: 27.7 g; 240 cm: 66.5 g). The duration was calculated by dividing the mass of the column of one-square centimetre for each height by the average grams of carbon per cubic centimetre per year added to the peatland (average of peat addition rates in Table 2). The error was calculated by dividing the standard deviation of the results by the average of the results.

Results

The exposed stratigraphic interval at the Beaver Pond site can be broken down into six units, all of which are present in Section A (Figure 5). The units, designated I – VI can be characterized based on differences in general lithology (i.e. sand dominated vs. peat dominated), sedimentology and loss on ignition characteristics. Units I and II extend laterally over sections A, C, E, and F while units III and IV are restricted to Sections A, B, and D. Units V and VI are only observed in Section A (Figure 5). The general

lithology of the Beaver Pond site is composed of quartz rich sands. The peat units are variable stratigraphically and laterally.

The peat thickness within the measured section at the Beaver Pond site (Unit 3) is estimated to have accumulated over 20449 ± 4999 years (Fig 5). However, the thickness of the excavated peat section, now completely removed, is estimated to represent 49077 ± 11997 years of peat growth (Fig 3).

Table 3: Calculated duration of the Beaver Pond peats based on rates of mass accumulation of peat per square metre per year in Unit III. The error is one standard deviation.

Analogue Site no.	Duration 100 centimetres	Error $\pm$	Duration 240 centimetres	Error $\pm$
1	21167	5174	50800	12418
2	22543	5511	54104	13226
3	25914	6335	62195	15203
4	20240	4948	48575	11874
5	12379	3026	29709	7262
Average	20449	4999	49077	11997

Detailed Unit Description

The primary component of Unit I was medium grained (1.5–2 ϕ), subangular to subrounded, poorly sorted, quartz rich sand and subangular to subrounded 5–25 cm thick cobbles. Several 5–20 cm peat lenses are interspersed within this interval. No sedimentary structures were observed. The organic content was low (<5%) and carbonate content was generally around 4% (Figure 6). Peats observed in Unit I are interpreted as transported from a nearby aquatic environment and therefore are not *in situ*.

Characteristics of this peat include a golden to reddish brown colour and light density.

Figure 5: Sections A through F from the Beaver Pond fossil site, showing proposed stratigraphic correlation between sections. Height measured in centimetres.

The main component of the peat was moss, deposited in thin sheets. There was little coarse fibrous material or other plant debris except vegetative remains of an aquatic plant (possibly cf. *Potamogeton* sp.), which will be referred to as “Pondweed.”

Unit II was comprised of three beds: a two centimetre thick organic rich sediment layer at the base; a ten centimetre thick peat layer, the lowermost peat observed in any section and overlies the organic rich sediment layer; and a ten centimetre sand layer with subangular to subrounded cobbles and no sedimentary structures. The sorting varied from moderate, associated with the smallest grain size, to poor. The peat in this layer corresponded to a sharp decline of grain size from medium to fine to very fine sand (2–4 ϕ) and the highest organic content in any section (40–61%). The carbonate was generally around 4% except in Section A where it reached 7%. The characteristics of the peat in this layer varied laterally. The peat found in Section A varied from fibrous and springy to peat formed in sheets. In addition some peat consisted of only moss and pondweed while further down section, more terrestrial components such as *Betula* leaves were included. This suggests a fully aquatic to semi-aquatic/riparian habitat. These peats contrasted with the same unit found in Section C (Figure 5). This peat formed in thin sheets but moss is not a major component; rather it was dominated by twigs and other terrestrial matter such as *Betula* and *Vaccinium* leaves as well as *Menyanthes* seeds. This indicates that Section C was drier than Section A and was likely more terrestrial although still moist.

Unit III, the main peat accumulation, consisted of a one-metre (maximum thickness) peat layer (Figure 5). The peat contains a substantial amount of quartz-dominated sand and *in situ* beaver cut sticks. The sections that represent Unit III display a wide range of grain sizes (0.5–3.5 ϕ). The highest concentration of beaver cut sticks is

Figure 6: Section A particle size statistics and loss on ignition data correlated with the lithology of the section. Height measured in centimetres. Mean, sorting, skewness and kurtosis are expressed in Phi units (ϕ). Mode is expressed in microns.

observed in Section B (Figure 5). The accumulation of beaver cut sticks trends southeast and the sticks are mainly oriented in the same direction with some larger sticks perpendicular to the main accumulation (Figure 11). Variability within the peat unit was observed where organic rich sands separate peat layers. The sorting was generally poor except at 167 centimetres of Section A, where sorting was moderate. The increased sorting was associated with a decrease in grain size (3.2 ϕ). The organic content of the peat was high (17–38%), but less than in Unit II. In areas with organic rich sand, the organic content was as low as 5%. The carbonate in this unit was especially low (1.2–1.7%). The peat varied from fibrous mossy peat with aquatic plants such as *Menyanthes*, *Equisetum* and “Pondweed” to chunky peat with some terrestrial plant matter such as *Betula* leaves, larger twigs (five millimetre), along with *Larix* cones and needles. This peat was likely deposited in a semi-aquatic to riparian/terrestrial environment.

Unit IV was a complex unit that represented a change in the depositional environment. A thin, fine to very fine sand (2.7–3.7 ϕ) formed the base, and transitioned upward into an organic rich sand layer, containing many small, aligned twigs with small pieces of charcoal and other organic materials (Figure 7: insets). The sorting was generally poor except at 174 centimetres in Section A, where the sediment was well sorted and associated with the finest grain size. There were also small rounded pebbles and cobbles present (Figure 7b). This unit weathered to a grey colour, something not observed anywhere else in the section. The organic content ranged from 10–18% and the carbonate varied from 1.0–1.9%. Higher carbonate contents occurred at 75 centimetres of Section B and 37 centimetres of Section D (3.5% and 6.9% respectively) and were associated with low organic contents.

Figure 7a: Detailed stratigraphy of Section A outlining peat types. Sample intervals marked by stars. Refer Figure 7b inset to see detail on Unit 4.

Figure 7b: Sedimentological Units I through V found at the Beaver Pond site. Note the cobbles indicated green arrow. The inset is Unit 4 to show alignment of twigs and charcoal (indicated by the red arrow)

Unit V consisted of a mixture of organic rich and pure yellow quartz sands while Unit VI consisted of pure quartz rich yellow sands. There were no visible sedimentary structures in either unit. The sands in both units were medium grained and poorly sorted. Unit V is slightly more organic rich than Unit VI (1.4–3.9% vs. 1.2–1.6%) and slightly more carbonate rich. Unit VI was overlaid by coarse grained sediment of unknown age and possibly of slumped origin (Figure 5).

Stick count data displayed in Figure 8 shows the largest accumulation of both beaver cut and non-beaver cut sticks occurred in the main peat accumulation. Note that many sticks have been removed in previous excavations and these counts refer to the remaining *in situ* sticks found at the Beaver Pond site (Figure 3). No beaver cut sticks were found in Sections E or F. All sticks in the main peat accumulation were counted within Unit III. There was a total of 30 beaver cut sticks and 107 non-beaver cut sticks.

Figure 8: Counts of beaver cut and non-beaver cut sticks within Unit 3. Section A is located at two m; B at four m and; D at five m.

Diatoms

The diatom assemblage recovered from the Beaver Pond site represented mainly extant freshwater taxa that can be commonly found in the High Arctic today (Antoniades et al., 2008). The number of diatoms observed in the samples ($n = 44$) was insufficient to apply statistical methods. The quality of preservation varied from fragmented valves to intact, very well preserved diatoms. No evidence of dissolution (i.e. pitting of valves) was observed (Plates 1–3).

The majority (95%) of diatoms were recovered from Section A (Figure 9). In total 19 species that belonged to 12 genera were identified. The basal 70-centimetres of the Section A was dominated by *Eunotia* spp. and small araphid “fragilarioid” species. *Pinnularia borealis* was present in the lowermost portion of the section. The greatest concentration of diatoms in this interval (0–74 cm) correlated with the onset of peat formation at the Beaver Pond site (52 cm).

In Section A, diatom counts increased within the thickest peat accumulation (74–168 cm). At the onset of this peat unit taxa included *Staurosira venter* sensu lato, *Fragilaria* sp. and *Achnantheidium* sp. No *Eunotia* sp. were found in this interval (74–112 cm). The only centric diatom observed, *Cyclotella bodanica* var. *lemanica*, occurred at 92 and 147 cm. At 132 cm the species richness increased as *Eunotia* taxa re-appeared. Other taxa that appeared for the first time in the uppermost section of this peat unit included *Tabellaria* sp., *Stauroneis* sp., and *Stenopterobia* sp. In the interval 168–184 centimetres, *Tetracyclus* sp. and *Eunotia* spp. were the only taxa recovered. Two other diatom taxa were found in other sections. *Ellerbreckia arenaria* f. *teres* was found at 49 centimetres

Figure 9: Diatom compositional changes in Section A showed a change in pH and nutrient content through time.

Plate 1: Diatom taxa from the Beaver Pond site on Ellesmere Island. Scale bars are five μm . 1–3: *Staurosira ventor*. 4–6: *Fragillarioid* taxa. 7: *Fragillaria* sp. (side view). 8: *Cymbella* sp. 9–10: *Achnanthidium* sp. 11: *Tabellaria flocculosa*. 12: *Tabellaria* sp. fragment.

Plate 2: Diatom taxa recovered from the Beaver Pond site on Ellesmere Island. Scale bars are five μm . 1a,b: *Eunotia monodon*; 2–3: *Eunotia inscisa*; 4–5: *Eunotia* sp.; 6: *Pinnularia borealis*; 7: *Ellerbreckia arenaria*; 8–9a, b: *Cyclotella bodanica* var. *lemanica*.

Plate 3: Scanning electron microscope plates of microfossil assemblage recovered from the Beaver Pond site. All scale bars are five um except plates 5–6 where the scale bar is ten um. 1–2: Unidentified algal cysts; 3: *Tetracyclus emarginatus*. (septa); 4–6 Freshwater sponge megascleres; 7–8: *Ephydatia mulleri* gemmoscleres.

in Section E while *Denticula* sp. was found at 110 centimetres in Section C. Neither was observed in Section A, where all other diatom taxa were recovered.

Other Siliceous Microfossils

Numerous other siliceous microfossils were observed in samples of the Beaver Pond site sediments (Plate 3). Two freshwater sponge taxa (Porifera: Spongillidae) were identified based on anatomical features of gemmoscleres and rotules. *Ephydatia mülleri* was the most abundant sponge (n = six), and was only observed in Section A. Many sponge megascleres and microscleres, which resembled *Ephydatia mülleri*, were observed in Section A, but most were broken allowing for only tentative identification. One *Ephydatia* cf. *fluviatilis* specimen was found in Section A.

Crysophyte cysts were common throughout Section A. No cysts were identified because the cysts cannot be linked to corresponding taxa to make paleoenvironmental inferences. Cyst preservation varies from broken to perfect. The cyst morphologies were spherical to oval with variable pore morphologies. Some phytoliths were observed while one protozoan (Protozoa: Rhizopoda) apertural plate has been identified as *Euglypha* spp. Some microfossils found in the Beaver Pond peats are presented in plates (above).

Discussion

The fossil assemblage recovered from the Beaver Pond site on Ellesmere Island reflects a Pliocene climate that supported rich Arctic ecosystems adapted to annual mean temperatures estimated from 0.5–1.4 °C (Ballantyne et. al., 2010, Czank et al 2011a). Fossil discoveries from this site have contributed to the paleoenvironmental interpretation of this Pliocene aged habitat; however very limited attention has been placed on the peat

deposits where most specimens were recovered. The expanded stratigraphic analysis of this study adds to our understanding of the site's complex depositional history. Previous interpretations addressing the fossiliferous peat unit suggested various depositional systems including oxbow lakes in braided river systems and floodplains in valley bottoms (Csank et al. 2011, Ovenden, 1993). *Scorpidium scorpioides* is the dominant bryophyte taxon at the Beaver Pond Site, a moss that is primarily found in extreme rich fens (Alice Telka personal communication, 2011). The moss assemblage indicates that the peat was formed primarily in a shallow water deposit (Ovenden, 1990). Fens typically have a slightly acidic (poor fen), circumneutral (rich fen) or alkaline (extreme rich fen) pH, are primarily ground water fed (geogenous), and can be forested or not. Today, forested fens are usually dominated by spruce (*Picea* spp.) and larch (*Larix* spp.), which are often found in stunted condition (Sharitz & Pennings, 2006). At the Beaver Pond site larch (*Larix groenlandii*), spruce (*Picea*), pine (*Pinus* cf. *pumila*), alder (*Alnus*), and birch (*Betula*) have been identified some of which were stunted (Matthews & Ovenden, 1990, Ovenden, 1993). Dwarf birch, a plant common to the margin of wetlands, is also very common (Robin Smith personal communication 2012).

Paleoenvironmental Change

Whereas previous paleoenvironmental interpretations of the Beaver Pond site were restricted to the peat horizon, the expanded stratigraphic section of this study reveals a more complex paleoenvironmental history of the site over time. Over the entire stratigraphic sequence as measured in the outcrop, five sedimentologically distinctive units were identified. These units attest to paleoenvironmental changes and the variety of

ecosystems that once characterized the Beaver Pond site. The poor sorting of sediments, presence of cobbles mixed with coarse sand and a lack of sedimentary structures of Unit I is indicative of flood plain deposits. The presence of the diatom *Pinnularia borealis* indicates that the area was moist. Lenses of well-preserved peat indicate the presence of nearby wetlands where rip-up peats might have originated (Figure 10 i). Transportation of the lenses likely occurred as periodic/seasonal flooding deposited as overbank deposits. The source of the cobbles is uncertain. A cobble conglomerate layer separates the Mount Moore and Margaret formations at Strathcona Fiord (Figure 2) (Miall, 1986). Although it is widely recognized that the Beaufort Formation downcuts into the Eureka Sound Group, the extent of the downcutting is not likely to have reached this cobble-rich boundary at Strathcona Fiord (Matthews & Ovenden, 1990). There is no evidence of a high-energy fluvial system in which these cobbles would have been transported leaving the hypothesis of possible ice transport. At the nearby Fyles leaf bed site, dated to 3.8 MY, evidence of permafrost suggests that there was seasonal ice in freshwater ecosystems of the area (Gosse & Rybczynski, 2011). The combined evidence suggests that Unit I represented a floodplain that was occasionally flooded by a river system and that the sediment source may have been of glacial origin (Figure 10 i).

The sediments in the peat of Unit II are a minor component of the matrix. The uniform and small sediment size in Unit II indicates that the sediment source is consistent and unchanging throughout the formation of the unit (Figure 10 ii). The diatom taxa found in the transition from Unit I to Unit II indicate the environment was circumneutral and oligotrophic compared to the rest of the section. The peat in Unit II may have formed due to an increase in the local water table to create an isolated rich fen.

Unit III is the main peat interval with poorly sorted sediment indicating influence from an outside sediment source. A fossil occurrence of a 20-cm percid fish suggests a larger water body (Murray et al., 2009). The presence of acid tolerant diatoms like *Eunotia monodon* (present day pH optima 6.5 $\pm$ 1.1) and *Eunotia incisa* (present day pH optima 5.2–5.3 $\pm$ 0.8) towards the top of Unit III indicates a shift from circumneutral conditions to more acidic conditions, relative to the rest of the section (Siver et al. 2005; Siver & Hamilton 2011). The lowering of pH is also supported by changes in the carbonate and organic matter composition (Figure 7). There are three sources of carbonate in freshwater lakes: production of skeletal elements, support structures and byproducts of living organisms; inorganic precipitation of carbonate minerals; and allochthonous carbonate transported into the lake (Kelts & Hsu, 1978). As organic matter exceeds 12% the pH decreases to a point that calcium carbonate at the surface–water interface dissolves (Dean, 1999). In general, the carbonate content of a lake is inversely proportional to the organic content (Dean, 1999). Since vertebrate fossils are preserved very well it is not likely that the peatland was necessarily “acidic” but the relative pH of the water did decrease and prevented aqueous carbonate from forming in situ. Also the presence of *Scorpidium scorpioides* is indicative of extreme rich fens, which are typically more alkaline environments (Sharitz & Pennings, 2006). Diatom taxa also indicate that the environment became slightly more nutrient rich when compared to Units I and II. The presence of the centric diatom *Cyclotella bodanica* var. *lemanica* suggests that a deeper water, lentic aquatic system existed at the Beaver Pond site. Unit III is interpreted as a small shallow lake with fluvial input delivering a sediment load

(Figure 10 iii). The peat could have formed in a shallow area or could have been formed as a floating mat (Ovenden, 1993).

Comparison of floral and faunal elements of the Beaver Pond site shows different preservation stages. Tree elements, leaves and cones for example are well preserved and have to be regarded as *in situ*. In contrast, vertebrate elements are mainly fragmented and fluvial transport into the system cannot be excluded. Stages of increased flow during peat accumulation are suggested by frequent sand layers interbedded with peat rich layers. In addition, predation as supported by the presence of predators such as fossil bear might have played a role as well in fragmenting vertebrate fossil content.

Based on floral and faunal fossil content discovered at the Beaver Pond Site, and comparisons to nearby stratigraphically correlative locations, previous investigators have attempted to interpret the site's ecological characteristics (i.e biomes, ecotones etc). Matthews and Ovenden (1990) suggested that floras compositionally similar to those associated with the Beaver Pond site occurred at a number of high-level alluvium sites of which many appear to represent near tree line conditions. This interpretation was confirmed by Dawson & Harington (2007) and Elias & Matthews (2002). Contemporaneous fossil localities 20–100 kilometres from the Beaver Pond site preserve plant and arthropod remains typical of the forest floor in coniferous forests today such as the plant *Epipremnum crassum* (Matthews & Ovenden, 1990; Ovenden, 1993).

If these contrasting sites did occur at the same time it would be unlikely that some sites would exist near tree line while others were in a larch dominated forest. It is much more likely the regional landscape consisted of a mosaic of a boreal-type forest mixed with tundra-like scrub. It has been hypothesized that a coniferous forest reached the

margin of the Arctic Ocean during the Pliocene and that the tundra and polar desert biomes were essentially eliminated in North America (Dowsett et al., 1999). This resulted in unique floral combinations that do not occur today. One such example present at the Beaver Pond site is the presence of *Saxifraga oppositifolia* and *Thuja occidentalis* (Matthews & Ovenden, 1990). Environmental conditions that are used to define modern biomes (i.e. precipitation, temperature) did not apply to the same Northern regions during the Pliocene.

The relatively sharp transition between Units III and IV signals a paleoenvironmental change that significantly reduced peat accumulation. There are no sedimentary structures within the sandy matrix, but the alignment of twigs and organic matter suggests flow in form of a creek or small stream (Figure 10 iv). The presence of cones and other organic matter as well as an abundance of charcoal within the layer suggests a nearby forest setting marked by occasional fires. Extensive forest fires have the capability to significantly alter the hydrologic conditions of a region and may have contributed to the end of peat formation at the Beaver Pond site. For example, evidence of extensive coal seam fires was reported from the Vendom Fiord area of Ellesmere Island dated at 3.3 ± 0.5 MY (Estrada et al., 2009). This locality is approximately 130–kilometres away but with fires extensive enough to ignite Eocene aged coal seams and to thermally alter rock, it is entirely possible that such fires altered the hydrologic conditions in the region that supported the Beaver Pond peat and ended paludification as well as destroyed the forest that surrounded the Beaver Pond site. In severe fires within peatlands combustion of the peat is common but that is not evident at the Beaver Pond site (Turetsky & St. Louis, 2006). There is abundant evidence of beaver activity at the Beaver

Pond site. Forest fires are known to decrease the occupancy rate of modern beaver colonies in an ecosystem, and may have been a factor that could have been influential in the abandonment of beaver activity at the site, which was followed by the reestablishment of a small fluvial system. (Hood et al., 2007).

The diatom assemblage found in the sediments of the Beaver Pond site can be broken down into transitional communities based on environmental preferences. The bottom of the section was dominated by *Staurosira venter* along with *Fragilaria* spp., and *Eunotia* spp. *Staurosira venter* is typically found in colder and harsher environments (Paull et al., 2008; Wolfe, 2000). The uppermost peat is dominated by more acid tolerant species such as *Eunotia incisa* and *E. monodon* along with *Tetracyclus emarginatus* (Siver and Wolfe, 2007). In addition, these taxa, especially *T. emarginatus* and *Achnantheidium minutissimum*, are reflective of shallower environments. Fens are not typically acidic environments but a decrease in pH is reflected by the diatom assemblage in the Beaver Pond strata and indicates a change in water conditions. This change can be explained by typically lower pH ranges in tundra beaver ponds or could be associated with acid run-off in areas of increased soil acidification due to the presence of coniferous trees (Paul Hamilton, personal communication, 2012). One cause for more acidic conditions at the Beaver Pond site could be the establishment of a larch dominated forest (Ford, 1990; Matthews & Ovenden, 1990). The freshwater sponge *Ephydaita mulleri* found throughout the peats at the Beaver Pond site is a holarctic taxon that prefers a slightly acidic dystrophic habitat (Økland & Økland, 1996; Frost & Ricciardi, 2001).

Peat Duration Estimates

The 240-centimetres of peat at the Beaver Pond site did not represent its original thickness due to burial by younger sediments and compression due to glaciation. Peat is amongst the most compressible sedimentary materials (van Asselen et al., 2010).

Although the depositional and climatic history of the Beaver Pond site may indicate that the peat has undergone extreme compression, there is some evidence that this is not the case. Some of the vertebrate fossils exhibit deformation or breakage but most of the sticks at the site are in very good condition (i.e. unbroken and with bark). The compressibility of the peat likely contributed to the preservation of the fossils after burial. Note that compression of the peat did not alter the mass of the peat, which was used in the following duration calculations.

Based on modern evidence as outlined in Table 3 the growth of peats at the Beaver Pond site grew over a period of a maximum of approximately 49000 ± 12000 years. Modern fen analogues of less than 10000 YBP commenced after the most recent ice ages and persist until the present (Yu et. al., 2003; Yu, 2006; Jones & Yu, 2010). The duration of modern northern peatlands is limited to the Holocene and climatic stability. During the Pliocene, the climate may have been stable enough to allow peatlands to span long periods of time up to an estimated 49000 ± 12000 years as outlined in Table 3 (Lisiecki & Raymo, 2007).

- iv - Dam removed, evidence of forest fires.
- Creek with flow established.
- Trees nearby.

- iii - Dam construction allowed expansion of wetland at the Beaver Pond Site.
- Sediment input from main channel.
- Trees in riparian zone.

- ii - Site located in a peatland isolated from floodplain.
- No sediment input from outside.
- Trees nearby

- i - Site located in a floodplain.
- Nearby peatlands in contact with river upstream.
- Delivery of peat lenses via river into floodplain.

X - Locality of sampling at Beaver Pond Site

Figure 10: Summary of environmental change that occurred at the Beaver Pond site correlated with the stratigraphy.

Role of Beavers in Pliocene High Arctic Wetlands

The presence of numerous beaver-cut sticks within the peat at the Beaver Pond site points towards the question of the role of fossil beavers in ancient ecosystems. The accumulation of beaver cut sticks in Unit III trended southeast and the sticks are mainly oriented in the same direction with some larger sticks perpendicular to the main accumulation. An accumulation that has since been excavated, measuring 72-centimetres long by five centimetres wide, was previously suggested as a possible core of a beaver made dam but conclusive evidence was lacking (Tedford & Harington, 2003; Harington field notes, 2001). Csank et al. (2011b) suggested that the peat accumulation found at the Beaver Pond site “likely represents an oxbow lake deposit formed when a beaver dam was built across one of the channels” without providing any evidence for dam building. The following discussion provides evidence for the hypothesis that the accumulation of beaver cut sticks may have been a beaver made dam.

Although much of the site has already been excavated for vertebrate fossils and many sticks have been removed, an accumulation of numerous beaver-cut sticks remains *in situ* (Figure 11). During previous excavations, the presence of numerous cobbles among the beaver cut sticks was noted and suggestions made that this accumulation represents an ancient feeding pile or possibly a core of a dam (Harington, 2001; Tedford & Harington, 2003). Cobbles and larch wood are common structural components in modern beaver dams in peatlands (Westbrook, personal communication, 2012). There is also evidence of beaver gnawing on fully-grown but stunted larch trees. Larch could have been used as food as evidenced from bilateral cut marks or for construction purposes. There is evidence of debarking on a small number of sticks for possible

consumption by *Dipoides* (Rybczynski, 2008). Alternatively the presence of bark on many of the beaver cut sticks suggests a still water environment that could form through damming. The lack of transport (i.e. fluvial) could indicate a low energy environment such as a beaver made pond (Rybczynski, 2008), a finding consistent with the diatom community. The fossil beaver *Dipoides* sp. found at the site is known to be a woodcutting semi-aquatic lineage of beaver, which could have used deeper water to forage or avoid predators (Rybczynski, 2007).

In Unit III, the medium grained, poorly sorted sediment indicated that there was a continuous fluvial sediment input into the fen. The organic content in this part of the section may be lower because of sediment trapping which would dilute the organic content. Dam building of modern beavers is associated with increased sedimentation rates due to sediment trapping as seen when comparing Unit II to Unit III (Naiman et al. 1986). The depth of the water as evidenced by planktonic diatom taxa and presence of a large perciform fish present in Unit III is additional evidence that sudden damming could have occurred. Modern beaver ponds have two possible outcomes. Either they fill-in and turn into a nutrient rich beaver meadow; or the dam fails, draining the pond (Butler, 1995). Given that modern beavers are a keystone species, when a beaver pond is drained it eventually returns to pre-beaver conditions and the system will cease to support lentic dependent taxa. Typically dam failure is due to abandonment and as previously mentioned, fire is associated with a decrease in the occupancy rate of beaver ponds (Hood et al., 2007). The evidence of fire and re-establishment of a fluvial system supported by twig alignment in Unit IV may be related to beavers abandoning the Beaver Pond site (Estrada et al., 2009).

Figure 11: Top – Northwest-southeast trending accumulation of beaver cut sticks. Note some larger sticks are perpendicular to the majority of the accumulation. Bottom: Remaining accumulation of sticks at the Beaver Pond site that show clear evidence of beaver cutting.

The number of beaver fossils recovered from the site suggests that more than one individual lived in the area. Living in family groups is an ancient trait of beavers that extends 23 Ma into the fossil record and would have been necessary for building and maintenance of a dam (Hugueney & Escuillie, 1995). The diversity of other vertebrate fossils found at the site suggests that, like the modern beaver, *Dipoides* sp. may have been an ecosystem engineer and a keystone species. This could be a reason why there was such a rich collection of Pliocene vertebrate fossils found at this locality. Modern beavers change their environment from a lotic system to a lentic one which creates new biological conditions that support a much wider array of wildlife than the original ecosystem (Collin & Gibson, 2001).

Peatlands are commonly initiated before beavers enter the system (Gorham et al., 2007). Contrarily it is also known that beavers create hydrological conditions conducive to wetland formation that persist over large spatial scales and long periods of time (Westbrook et al. 2006). Both situations are plausible at the Beaver Pond site. The stratigraphy presented in Figure 5 shows the main accumulation of beaver cut sticks and the occurrence of a possible dam in Unit III but peat development started earlier in Unit II. The wetland at the Beaver Pond site could have developed naturally and *Dipoides* inhabited the system after initiation or the peatlands were initiated by beaver activity nearby and occupied the Beaver Pond site later. Currently it is impossible to tell which situation occurred but either possibility presents evidence that beaver activity played a major role in the persistence of the Beaver Pond site.

An alternative to the beaver dam hypothesis is a small logjam. This is not likely because of the amount and good condition (i.e. bark) of the beaver cut sticks in the

accumulation as well as the duration of the system. If this was a logjam, it might be related to seasonal flooding events where sticks/small trees are transported downstream of the source. This requires a significant amount of energy in the system, something that is not reflected in the sedimentological record at the Beaver Pond site. Also, the number of beaver cut sticks and *Dipoides* sp. fossils indicate this was an established aquatic ecosystem, not a unique event such as a logjam.

There is no conclusive evidence to confirm or refute the possibility that the accumulation of beaver cut sticks at the Beaver Pond site represents a fossilized beaver dam. Other possibilities for the origin of the accumulation of beaver cut sticks could include the remnants of a feeding pile (Harington, 2001) or part of a lodge. However, it can be stated that *Dipoides* sp. likely helped maintain the duration of the Beaver Pond site as a keystone species. These are important ecological findings to consider when explaining Neogene and Quaternary paleoenvironmental changes because of the profound impact modern beaver are known to have on their ecosystems.

Conclusions

By describing the stratigraphy, this paleoenvironmental study has characterized the depositional history of the Beaver Pond site. Field observations indicated that the site is *in situ*, not slumped, which provides confidence in the stratigraphy. The sedimentological history is variable and quite complex, which reveals the potential for ecosystem change over a short period of time. The peats deposited at the Beaver Pond site extended over a period of a minimum of approximately 20450 ± 5000 to a maximum of 49000 ± 12000 years. Six different sedimentological units were identified based on

lithological changes throughout the section. This study shows that the ecosystem transitioned from a fluvial setting into a wetland that attracted wildlife then back to small creek. These changes may have been influenced by ecosystem modification by the fossil beaver *Dipoides* sp. Environmental conditions such as forest fires have also been shown to be influential in the environmental change observed at the Beaver Pond site. The ecological boundaries (i.e. biomes, ecotones) as defined by various environmental parameters today (i.e. precipitation etc) did not apply to the Pliocene High Arctic and the treeline was north of the Beaver Pond site at the time of formation.

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Appendix A: Sedimentological and LOI characteristics of sections B through F.

Figure A: Section B particle size statistics and loss on ignition data correlated with the lithology of the section. Height measured in centimetres. Mean, sorting, skewness and kurtosis are expressed in Phi units (ϕ). Mode is expressed in microns.

Figure B: Section C particle size statistics and loss on ignition data correlated with the lithology of the section Height measured in centimetres. Mean, sorting, skewness and kurtosis are expressed in Phi units (ϕ) . Mode is expressed in microns.

Figure C: Section D particle size statistics and loss on ignition data correlated with the lithology of the section. Height measured in centimetres. Mean, sorting, skewness and kurtosis are expressed in Phi units (ϕ). Mode is expressed in microns.

Figure D: Section E particle size statistics and loss on ignition data correlated with the lithology of the section. Height measured in centimetres. Mean, sorting, skewness and kurtosis are expressed in Phi units (ϕ). Mode is expressed in microns.

Figure E: Section F particle size statistics and loss on ignition data correlated with the lithology of the section. Height measured in centimetres. Mean, sorting, skewness and kurtosis are expressed in Phi units (ϕ). Mode is expressed in microns.

Appendix B: Data from peat duration calculation and density calculation.

Table A: Data for calculated duration of 100-cm of Beaver Pond site peat based on rates of peat addition per square metre per year.

no.	(g Carbon /m2/year)	(g Carbon /cm2/year)	Thickness of fossil peat (cm)	Volume of column of fossil peat (cm3)	Fossil peat density (g/cm3)	mass of column of fossil peat	Duration	Error ±
1	13.1	0.00131	100	100	0.277	27.7	21166	5174
2	12.3	0.00123	100	100	0.277	27.7	22543	5510
3	10.7	0.00107	100	100	0.277	27.7	25914	6334
4	13.7	0.00137	100	100	0.277	27.7	20239	4947
5	22.4	0.00224	100	100	0.277	27.7	12378	3025
Average							20448	4998

Table B: Data for calculated duration of 240-cm of Beaver Pond site peat based on rates of peat addition per square metre per year.

no.	(g Carbon /m2/year)	(g Carbon /cm2/year)	Thickness of fossil peat (cm)	Volume of column of fossil peat (cm3)	Fossil peat density (g/cm3)	mass of column of fossil peat	Duration	Error ±
1	13.1	0.00131	240	240	0.277	66.5	50800	12418
2	12.3	0.00123	240	240	0.277	66.5	54104	13226
3	10.7	0.00107	240	240	0.277	66.5	62195	15203
4	13.7	0.00137	240	240	0.277	66.5	48575	11874
5	22.4	0.00224	240	240	0.277	66.5	29709	7262
Average							49077	11997

Table C: Density calculations for peat samples used in Duration calculations.

Sample ID	Dry Mass (%)	dry mass (g)	Volume (cm3)	Fossil peat density (g/cm3)
A11	67.20582289	4.946	7.62	0.44
A12	73.71991247	4.57	5.81	0.58
A13	75.35221289	7.027	9.08	0.58
A14	75.43278085	8.145	9.93	0.62