

Ecological influences of Thule Inuit whalers on high Arctic pond ecosystems: a comparative paleolimnological study from Bathurst Island (Nunavut, Canada)

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Abstract Until recently, major anthropogenic impacts on freshwater ecosystems were believed to be rare in North America prior to the period of European colonization. However, recent paleolimnological and archaeological data collected from the Canadian Arctic suggest that the whaling activities of Thule Inuit, who lived in small, nomadic communities, altered freshwater ecosystems centuries earlier. Using a comparative paleolimnological approach from two ponds situated adjacent to a former Thule winter settlement on south-eastern Bathurst Island (Nunavut, Arctic Canada), we record marked ecological changes in pond ecology due to eutrophication from the Thule's activities. The geography of our study site provided an interesting and rare opportunity for a

comparative paleolimnological study of long-term Thule impacts on polar limnology, because our two study ponds (only ~50 m apart) were nearly identical in size and in geological and climatic settings, but differed markedly in the magnitude of Thule influence. Here, we recorded striking changes in diatom species assemblages, spectrally-inferred primary production, and nutrient geochemistry, indicating eutrophication in a small pond draining 18 Thule whale houses. Input of marine-derived nutrients from sea mammal carcasses used by the Thule for both sustenance and the construction of winter settlements, as well as other anthropogenic activities, coincided with a notable increase in the eutrophic diatom taxon *Stephanodiscus minutulus*, whereas no comparable changes were recorded in the nearby control pond for the duration of the sedimentary record. Although the diatom changes recorded in the affected site persisted after the period of Thule occupation, the most recent sediments and water chemistry suggest that the pond has largely recovered to near pre-impact conditions.

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Introduction

Paleolimnology presents an interesting opportunity to study long-term environmental changes, allowing

researchers to use a variety of physical, chemical and biological indicators archived in the sediment record to investigate environmental perturbations beyond the historical record (Smol 2008). These techniques are particularly important in Arctic environments where we seldom have limnological data collected for more than 1 year (if at all), and long-term monitoring data are therefore completely lacking. However, because of their sensitivity to environmental variables such as pH, salinity and nutrient concentration (e.g. nitrogen and phosphorus), algal indicators, and especially diatoms, are being used increasingly as early indicators of change due to a variety of natural and anthropogenic stressors (Smol and Stoermer 2010).

Diatoms have been used increasingly in the past several decades to assist researchers in studying the impacts of numerous stressors such as acidification (Battarbee et al. 2010), eutrophication (Hall and Smol 2010) and anthropogenic climate warming (Rühland et al. 2003, 2008; Smol et al. 2005) on aquatic ecosystems. Their usefulness specifically in polar regions as paleolimnological indicators has recently been reviewed by Douglas et al. (2004b). In addition to morphological indicators such as diatoms, sediment geochemistry is being increasingly used by paleolimnologists to track marine-derived nutrients in freshwater systems. Marine-derived nutrients enriched in ^{15}N , from organisms high in the food web, such as anadromous salmon (Finney et al. 2000, 2002) and seabirds such as northern fulmars (Michelutti et al. 2009a), may be transported inland and deposited in freshwater aquatic systems. These nutrients lead to isotopically enriched sediment deposits which can be analyzed using paleolimnological techniques (i.e. coring and close-interval sectioning) and isotope ratio mass spectrometry. For example, using $\delta^{15}\text{N}$ from sediment cores, researchers have been able to track nutrient inputs into freshwater ecosystems from birds (Blais et al. 2005), whales (Douglas et al. 2004a) and sockeye salmon (Finney et al. 2002; Gregory-Eaves et al. 2003). Spectrally-inferred chlorophyll-*a* has also been used in the past as a proxy for whole-lake primary production changes (Michelutti et al. 2005; Wolfe et al. 2006), and has been shown to closely reflect changes recorded in other proxies for primary production such as total organic carbon (TOC) and biogenic silica (BSiO_2 ; Michelutti et al. 2005, 2009b).

Thule Inuit culture represents one of the earliest examples of anthropogenic impacts on aquatic

ecosystems in North America. Recently, Douglas et al. (2004a) recorded major diatom species changes in a paleolimnological investigation of a freshwater pond near an abandoned Thule site on Somerset Island, Arctic Canada. Douglas et al. (2004a) showed that the onset of Thule occupation resulted in unprecedented ecosystem and other limnological changes attributed to nutrients released from slaughtered whale carcasses as well as other anthropogenic activities. Nutrient concentrations continued to remain high at Somerset Island site, ~400 years after the Thule abandoned the region. Although the Douglas et al. (2004a) study unequivocally showed that the Thule impacted the water quality of a freshwater pond, their study was limited to a single site near the southernmost range of the Thule people in the High Arctic islands, and thus the influence of the Thule on other freshwater sites throughout the vast Arctic remained unexplored. Here, we examine two ponds near the geographical centre of the Thule range, an archeological location known as the “Deblicquy site” on Bathurst Island, Nunavut (Fig. 1; Taylor and McGhee 1981; Le Mouel and Le Mouel 2002). The two ponds selected at the Deblicquy site are ideal to study the impacts of Thule whaling practices on freshwater ponds, as one of these sites received far greater input of nutrients from Thule

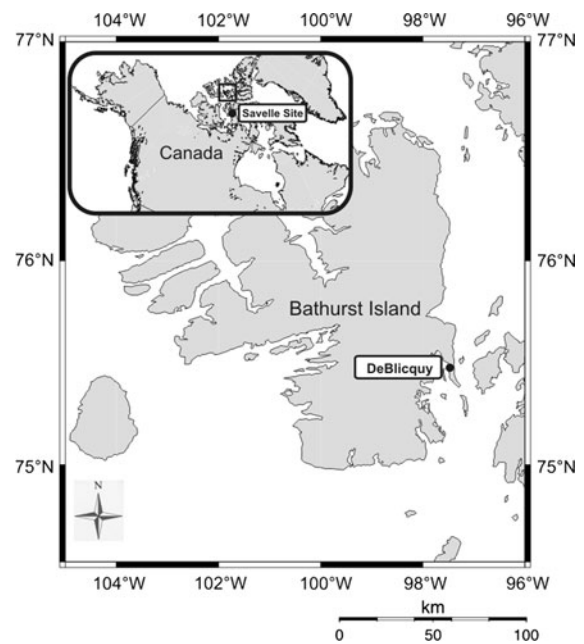


Fig. 1 Map of Canada/Bathurst Island showing the approximate location of the Deblicquy Site (75° 29' N, 97° 29' W)

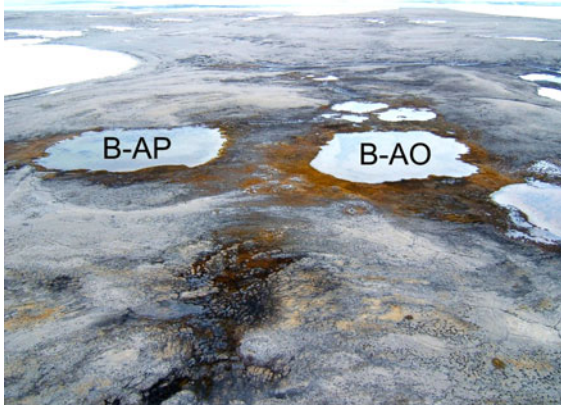


Fig. 2 Aerial photo of the Deblicquy site, showing both study sites (B-AO and B-AP) and the relative moss cover surrounding the two ponds. See Fig. 3 for scale

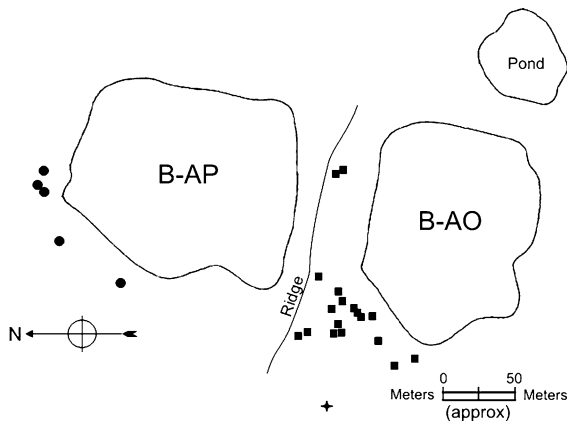


Fig. 3 Schematic representation of the Deblicquy Thule site from directly above. Individual houses have been indicated and coded based upon which pond they drain into. *Squares* B-AO, *Circles* B-AP and *Star* neither (Modified from Taylor and McGhee 1981)

activities (Figs. 2, 3). In essence, we are able to compare and contrast the paleolimnological records of two ponds of similar size, in similar geologic and climatic settings, but with the primary variable distinguishing the two ponds being the degree of Thule influence.

Thule culture and occupation of the study region

Thule Inuit migrated across the Arctic tundra from Alaska to Greenland arriving at the Deblicquy site ca. thirteenth or fourteenth century, bringing with them unprecedented whaling technologies (Taylor and McGhee 1981; McGhee 2000). Whaling

occurred primarily during ice break up as the whales entered the eastern Arctic in early summer, moving to their maximum western extent by mid-September (Savelle and McCartney 1999). Whaling parties, in multiple boats each consisting of a six- to nine-man crew, composed of a helmsman, a harpooner and numerous paddlers, hunted bowhead whales using a combination of harpoons, seal skin floats (to fatigue the whale and force it to surface) and a lance (Whitridge 2002). Whales were towed ashore, where they would be flensed and divided according to social hierarchy (Whitridge 2002). Following about 1400–1500 AD, the Thule culture began to decline and a transition to the historic Inuit occurred, who were more dependent on sealing (McCartney 1980; Whitridge 2002). This change in subsistence strategy is supported by research on the changing style of Thule winter dwellings (Schledermann 1976) and is generally believed to coincide with the onset of the Little Ice Age and the resultant changes in distribution of fauna (Schledermann 1976; McCartney 1977; Moore et al. 2001). How climatic conditions may have specifically affected the Thule movement through Arctic Canada is unknown; however, sea ice conditions would have been paramount in mediating such influence. McGhee (2009) has argued that the major shift in Thule Inuit occupation area and subsistence base during the sixteenth century may also have been influenced by a growing involvement in trade with Europeans.

Site description

Bathurst Island (Fig. 1) differs limnologically and ecologically from many of the other High Arctic islands. Soils in the low lying areas of the island, particularly the Polar Bear Pass region, are wetter and more developed than is typical of the High Arctic (Tarnocai 1976). These soil characteristics have contributed to an increased abundance of vegetation in this region and, as a result, atypical wildlife activity. Due to the influence of muskox and Peary caribou calving grounds in the Polar Bear Pass region, several of the ponds have higher than average nutrient concentrations (Lim et al. 2001). Outside the lush Polar Bear Pass region, the small- to medium-sized shallow melt-water ponds that dominate the Bathurst Island landscape are typically oligotrophic, alkaline, and dilute (Lim et al. 2001).

The Deblicquy site (75° 29' N, 97° 29' W; archaeological designation QiLe-12) is located on an unnamed point on the southern coast of Bathurst Island (Fig. 1). The Deblicquy site is ~22 m asl, 0.25 km away from the ocean, and is surrounded largely by grey limestone gravel (Taylor and McGhee 1981). The site was studied extensively during the 1960s by a small archaeological field crew, who camped on the dry gravel raised beaches outside the site area, and therefore would have had negligible effect on the ponds (Taylor and McGhee, 1981). During their survey, Taylor and McGhee (1981) identified 24 semi-subterranean Thule whale bone houses that are directly adjacent to two small (~90-m diameter) and shallow (~50-cm maximum depth) ponds, which we refer to as B-AO and B-AP, continuing the site-naming sequence used by Lim et al. (2001) for their Bathurst Island limnological survey (Fig. 1). Excavation of several of the 24 houses during the 1970s, and the subsequent study of artifacts associated with these sites, led researchers to conclude that Thule Inuit occupation of this site took place between the fourteenth and sixteenth century (Taylor and McGhee 1981). More recently, two radiocarbon samples of land mammal tissue associated with occupation of the Deblicquy site provided dates of 620 ± 40 (BETA 219190; calibrated AD 1297–1393) and 540 ± 40 (BETA 219191; calibrated AD 1325–1430), suggesting a fourteenth and fifteenth century span of occupation (McGhee 2009). These houses are situated such that the bulk of the nutrient input (16 houses) is directed towards B-AO, which is further reflected by greater moss growth around this pond. Meanwhile, only five houses drain directly into pond B-AP, whereas the two houses between the two ponds may contribute to both ponds (Fig. 3). This allows us to assess the impact of nutrients from Thule activities by comparing two ponds whose geology, climate and physical characteristics are nearly identical, but have had markedly different impacts from the Thule whalers.

Methods

Sediment collection, geochronology, and stable isotopes

Short sediment cores were collected from the deepest portion of each pond ($Z_{\max} = \sim 50$ cm) by wading out

and pushing a 3-inch (7.6-cm) diameter core tube into the sediment. Cores were sectioned on site at 0.5-cm resolution using a Glew (1988) vertical extruder, and the sediment sections were stored in Whirlpak® bags and kept cool and dark until returned to the laboratory.

Based upon the presence of marine diatom fragments in the bottom sections of the core, we can assume that we have obtained a near-complete record of both ponds histories since emergence from the ocean. However, sediment dating via both alpha and gamma ^{210}Pb techniques proved ineffective due to low activity, which is a very common problem in High Arctic environments (Wolfe et al. 2004). Similarly, the radiocarbon dating we attempted was also problematic, as it was in the Douglas et al. 2004a study, due to the absence of terrestrial macrofossils and the hard-water effect due to the high carbonate content of the region. Several bulk sediment and humic acid radiocarbon dating attempts were made; however, the dates were uncertain and did not serve to clarify the chronologies of our ponds. Therefore, similar to the Douglas et al. (2004a) study from Somerset Island, we used stable isotopes (i.e. anomalous increases in $\delta^{15}\text{N}$) to estimate the period of Thule occupation at our site, which could then be constrained by the radiocarbon dating of the archaeological artifacts in the catchment, as outlined above. As described in Douglas et al. (2004a), runoff from butchered sea mammals (whales, seal and walrus) would be enriched in ^{15}N . Based on the enrichment of ^{15}N due to marine-derived nutrient inputs in other studies (Finney et al. 2002; Douglas et al. 2004a; Blais et al. 2005; Michelutti et al. 2008), we have estimated the period of Thule occupation based on the 2–3‰ increases observed in the $\delta^{15}\text{N}$ of our sedimentary profile (Fig. 4). Because the timing of Thule occupation can be constrained by the radiocarbon dates of the archaeological artifacts, we use this as an indirect dating method in this paper.

For stable isotope analyses, sediments were analyzed for $\delta^{15}\text{N}$ at 1-cm intervals from 0.0 to 3.0 cm and 7.0 to 8.5 cm and at 0.5-cm intervals from 3.0 to 7.0 cm. Measurements were made at the G.G. Hatch Stable Isotope Laboratory (University of Ottawa) using a Vario EL III (Elementar, Germany) + ConFlo II + DeltaPlus XP IRMS (ThermoFinnigan, Germany) with analytical precision (2 sigma) of $\pm 0.2\text{‰}$. Freeze-dried sediment was weighed into tin capsules and flash combusted at 1,800°C in an

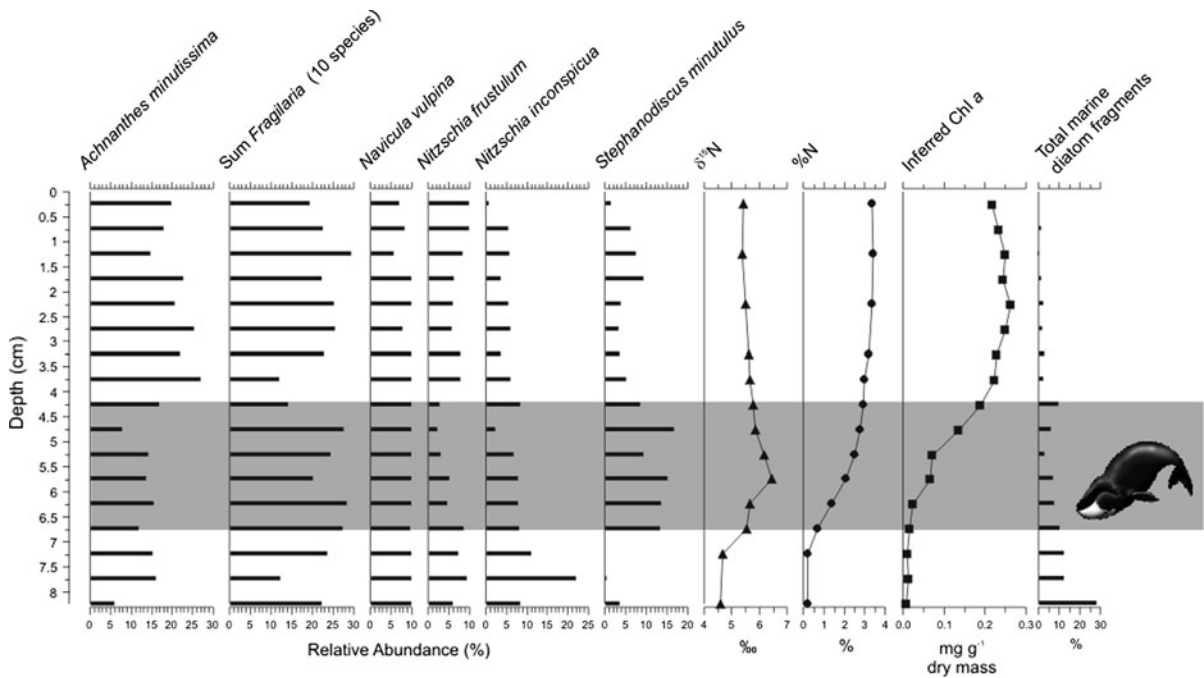


Fig. 4 Stratigraphic profile of the most abundant diatom taxa from pond B-AO and corresponding concentrations of $\delta^{15}\text{N}$, %N and spectrally-inferred Chl *a*. Shaded area represents the

estimated Thule period based on $\delta^{15}\text{N}$ changes. Marine diatom fragments are plotted as a percentage of the total number of diatoms counted

elemental analyzer (EA) or elemental combustion system (ECS). The resultant gases were carried via helium through the EA for purification and separation into N_2 and CO_2 and then into an isotope ratio mass spectrometer (IRMS) for isotope analysis via a ConFlo interface. Data were normalized using internal standards previously calibrated with International standards IAEA-CH-6, IAEA-NBS22, IAEA-N1, IAEA-N2, USGS-40, USGS-41.

Diatoms

For diatom analysis, ~0.3 g of wet sediments were digested with nitric acid using a CEM MarsX microwave digester (Parr et al. 2004), rinsed with deionized water until a neutral pH was achieved and permanently mounted on slides using Naphrax®. Diatoms were then enumerated at 1000× under oil immersion using a Leica DMR2 microscope with differential interference contrast (DIC). A minimum of 300–400 diatom valves were counted for each interval and identified using standard taxonomic sources (Krammer and Lange-Bertalot 1986–1991;

Cumming et al. 1995) except in a few cases where, due to extremely low diatom concentrations in older sediments in both ponds, diatom enumeration stopped once a minimum of 200 diatom valves was reached. Diatom valves were well preserved, suggesting that low counts were more likely the result of lower productivity and not an issue of poor preservation. In the interest of making the diatom profiles more readable, several (i.e. 10) small benthic *Fragilaria* taxa have been grouped for presentation in Figs. 4 and 5; full stratigraphies of these taxa can be found in Hadley (2007).

Spectrally-inferred chlorophyll *a*

Sediment used for spectral analysis was first freeze-dried and sieved through a <125- μm mesh. Using the Foss NIRSystem 500, measurements of absorption in the 400–1,100-nm range were taken and chlorophyll *a* (Chl *a*) concentrations were inferred based on the algorithm developed in Michelutti et al. (2005) and validated in several paleolimnological investigations (Wolfe et al. 2006; Michelutti et al. 2009b).

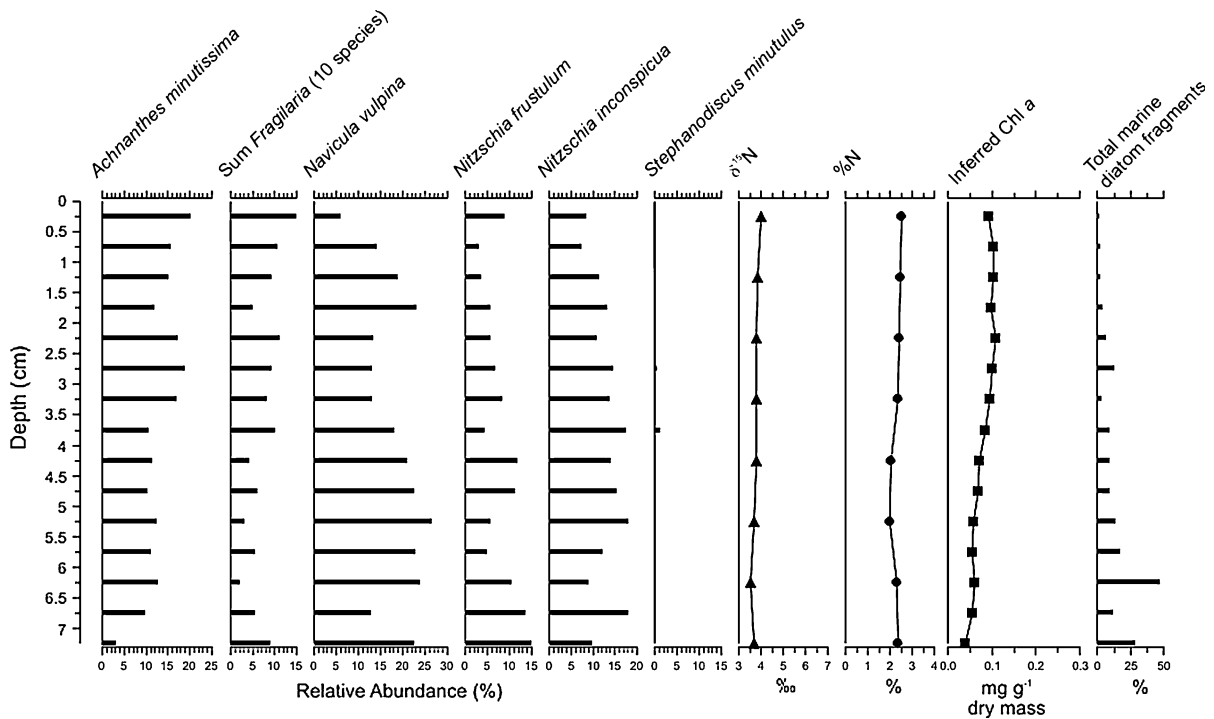


Fig. 5 Stratigraphic profile of the most abundant diatom taxa from pond B-AP and corresponding concentrations of $\delta^{15}\text{N}$, $\%N$ and spectrally-inferred Chl *a*. Marine diatom fragments are plotted as a percentage of the total number of diatoms counted

Results and discussion

Modern limnology

Both of our study ponds had slightly elevated levels of nitrogen, as well as high dissolved organic carbon (DOC), relative to the means calculated for Bathurst Island (TN = 0.577 mg/l, TP = 12.7 $\mu\text{g/l}$, DOC = 4.1 mg/l, $n = 38$) by Lim et al. (2001). Pond B-AO, the most highly influenced site, had 0.777 mg/l total nitrogen (TN), 15.4 $\mu\text{g/l}$ total phosphorus (TP) and 6.3 mg/l DOC, while pond B-AP had 0.721 mg/l total nitrogen, 14.8 $\mu\text{g/l}$ total phosphorus and 4.7 mg/l DOC. These values fall within the range of variability observed by Lim et al. (2001). Moreover, current nutrient concentrations of both B-AO and B-AP are very similar, despite the different levels of impact during the Thule period. Furthermore, these sites are not strikingly different from other Bathurst Island sites. These observations, coupled with an observed shift in diatom species assemblage towards pre-anthropogenic disturbance conditions in the upper part of the B-AO core (Fig. 4), suggest that partial chemical and

biological recovery may have occurred following the abandonment of this site by the Thule.

Paleolimnological proxies

Prior to Thule occupation, both our study ponds showed similar levels of aquatic production, as inferred by spectral reflectance, diatom species composition and nutrient geochemistry (Figs. 4, 5). Paleolimnological data observed in the earliest portion of both cores are consistent with pre-disturbance, oligotrophic, High Arctic pond ecosystems recorded in many other studies (Michelutti et al. 2000; Rühland et al. 2003). The pre-Thule diatom assemblages in both B-AO (Fig. 4) and B-AP (Fig. 5) are dominated by taxa such as small, benthic *Fragilaria (sensu lato)* species, *Nitzschia* species, *Achnanthes minutissima* (Kütz.) Czarn. (Synonym: *Achnanthidium minutissimum*) and *Navicula vulpina* Kütz., typical of those recorded in pre-Anthropocene High Arctic lakes and ponds (Michelutti et al. 2000; Rühland et al. 2003; Smol et al. 2005). During this period, both sites also had low inferred Chl *a* concentrations and typical

stable isotope nutrient geochemistry ($\delta^{15}\text{N} = \sim 3.5\text{‰}$), suggesting little marine-derived nitrogen input (Figs. 4, 5).

An increase of $\sim 2\text{‰}$ in the $\delta^{15}\text{N}$ of pond B-AO marks the beginning of Thule occupation at the 6.5-cm depth in our sediment core (Fig. 2). This increase in $\delta^{15}\text{N}$ represents a change similar in magnitude to that observed by Douglas et al. (2004a) with the arrival of the Thule Inuit on Somerset Island. Contemporaneous shifts recorded in multiple proxies coinciding with the beginning of the Thule period indicate that nutrient inputs from Thule activities (e.g. whaling, seal hunting, etc.) altered the ecology of pond B-AO (Fig. 4).

Pond B-AO, which received the majority of the Thule nutrient enrichment, showed marked changes in diatom species assemblages (Fig. 4), specifically an increase in the relative abundance of planktonic, eutrophic taxon *Stephanodiscus minutulus* (Kütz.) Cleve & J. D. Möll. (Cumming et al. 1995), a diatom which has seldom been observed in the High Arctic. Although very rare in Arctic ponds, *S. minutulus* has been widely observed and well described at southern latitudes in North America (Hall et al. 1997; Reavie et al. 2000) and Europe (Lotter 1998; Alefs and Müller 1999), where it flourishes in environments with elevated concentrations of nitrogen and phosphorus. The increased relative abundance of *S. minutulus* from 0 to $\sim 20\%$ in B-AO represents a significant ecological change resulting from the enhanced nutrient input into the system. Diatom assemblage changes observed in B-AO are more ecologically striking than those observed in the Savelle site on Somerset Island (Douglas et al. 2004a). Changes in diatom species assemblages as a result of cultural eutrophication have been previously documented in the Arctic on several occasions (Douglas and Smol 2000; Douglas et al. 2004a), however, these diatom species assemblage shifts have typically been limited to benthic taxa. Douglas et al. (2004a) attributed an increase in *Pinnularia balfouriana* Grun. ex Cleve. (Synonym: *Hygropetra balfouriana* (Grunow ex Cleve) Krammer & Lange-Bertalot) during the period of Thule occupation on Somerset Island to habitat changes, and specifically enhanced moss growth resulting from increased nutrients in the catchment. Here, for the first time in the Arctic, we see the beginnings of a regime shift with planktonic taxon increasing significantly in the paleolimnological record as a result of nutrient enrichment. Change of

this magnitude is not necessarily unprecedented in the Arctic during the Anthropocene, when human-induced climate warming has led to the increased dominance of oligotrophic, planktonic taxa in many Arctic lakes and ponds (Smol et al. 2005; Rühland et al. 2008). However, the B-AO profile records these striking changes centuries prior to significant anthropogenic climate impact.

An unprecedented increase in spectrally-inferred Chl *a* concentration also occurs in B-AO, concurrent with the changes in both diatom species assemblage and nitrogen stable isotope geochemistry, further indicating a significant change in the pond's ecology (Fig. 4). The timing of this change, prior to significant anthropogenic climatic warming, further suggests that the nutrient enrichment from Thule Inuit settlement is the root cause of the limnological changes observed at this site.

A marked decline in *S. minutulus* relative abundance at 4.0 cm in B-AO may indicate the end of the active Thule whaling period (Fig. 4), which archaeologists estimate ca. 1500 AD (Taylor and McGhee 1981). *S. minutulus* relative abundances no longer constitute a major ($>5\%$ relative abundance) portion of the diatom assemblage for the rest of the core.

In stark contrast to what was recorded in B-AO, our less impacted pond (B-AP) showed no major changes in geochemistry, nitrogen isotopes, or Chl *a* concentration (Figs. 4, 5). Profiles were essentially straight lines for the duration of the sedimentary record (Fig. 5). The same *Achnanthes*, *Fragilaria*, *Navicula* and *Nitzschia* taxa found in B-AO dominate the sedimentary record of B-AP. Variations in the relative abundances of these taxa occur throughout the core, however, no new dominant diatom taxa emerge (Fig. 5).

Conclusions

The distribution of the whalebone-framed houses at the Deblicquy site provided us with a unique opportunity to directly compare two very similar ponds, whose main distinguishing feature was the degree of past Thule Inuit whaling impacts. Concurrent changes in multiple paleolimnological proxies suggest that nutrient loading of marine origin (i.e. related to the bowhead whale and seal carcasses), associated with the Thule Inuit, resulted in marked limnological

changes in pond B-AO. Meanwhile, there is little to no change observed throughout the duration of the sedimentary record in the relatively unaffected site (pond B-AP).

Although there are some important differences in the site-specific responses to nutrient enrichment between our Thule site and the Somerset Island study, our paleolimnological data support the conclusions of Douglas et al. (2004a). Together these two studies, and similar studies on ancient cultural eutrophication (Ekdahl et al. 2007), serve to highlight the sensitivity of freshwater ecosystems to relatively minor anthropogenic disturbances and represent some of the earliest known anthropogenic impacts on North American ponds. Furthermore, these types of studies serve to build new research bridges between paleolimnologists and archaeologists, the results of which should be beneficial to both groups.

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