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Arctic lake ontogeny across multiple interglaciations

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ABSTRACT

Few lakes in the Arctic preserve sediments older than Holocene age because of pervasive glacial scour during the last ice age. Here we present sediment diatom and geochemical records from a lake on east-central Baffin Island (CF8, Nunavut, Canada) that captures three successive interglacial periods within the last 200,000 years: a portion of marine isotope stage (MIS) 7; the last interglacial (MIS 5e); and the Holocene (MIS 1). An additional unit of diatom-rich organic sediment occurs between the latter two intervals, and is ascribed to MIS 5a interstadial conditions. The Lake CF8 paleolimnological record reveals similar ontogenetic trends within each interglacial. Early postglacial environments in both the Holocene and MIS 5e were characterized by a dominance of colonial benthic fragilarioid diatoms that thrived in relatively alkaline waters. These species shifts do not coincide with major changes in base cation delivery to the sediments, suggesting that shifts in diatom assemblages are controlled mainly by climate-driven pH dynamics. Diatom assemblages then transitioned into dominance by tychoplanktonic *Aulacoseira* species, likely in response to climate-driven pH dynamics. The highest sustained abundances of *Aulacoseira* occur in sediments ascribed to MIS 5e, and this is the only interval in which thalassiosiroid centric taxa also occur (e.g. *Discostella* and *Puncticulata* spp.). Given that these planktonic taxa typically reach high abundances during extended periods of open-water conditions, we surmise that MIS 5e was the warmest interval recorded. The overall similarity of lake ontogenetic trajectories recorded within each interglacial period suggests that climatic and edaphic factors drive a complex succession of environmental changes through indirect effects on lake ice cover, habitat availability, and lake-water pH. In recent decades (past ~50 yrs), an unprecedented increase in periphytic *Eunotia* taxa is evident; these diatoms were only present intermittently during previous glacial–interglacial cycles. The expansion of *Eunotia* is attributed to increased habitat availability associated with declining ice cover during recent 20th century warming. By integrating data from several distinct interglacials, the CF8 diatom record considerably extends our understanding of Arctic lake ontogeny, and provides an unparalleled natural archive with which to compare recent changes associated with anthropogenic climate warming.

1. Introduction

Although it is recognized that greenhouse gas concentrations are closely coupled to global climate on Quaternary glacial–interglacial timescales (Petit et al., 1999; Siegenthaler et al., 2005), there is relatively little parallel data documenting terrestrial ecosystem development over successive interglacials (Woillard, 1978; Tzedakis, 1994; Brigham-Grette et al., 2007). This is particularly evident in high-latitude regions within glacial limits, where only scattered pre-Holocene non-marine sediments exist (Wolfe and Smith, 2004; Hodgson et al., 2006). Such records have the potential to provide baseline information concerning long-term natural ecosystem variability, to which any recent changes associated with anthropogenic activities can be compared. The recognized sensitivity of Arctic lakes to recent climate change, coupled to the paucity and short duration of monitoring data, mandates a need to develop and refine long-term proxy records (Smol et al., 2005; Smol and Douglas, 2007).

Holocene environments have been characterized across the Arctic, including eastern Baffin Island, the focus region of this

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present study, using paleoenvironmental and geological records (e.g. CAPE Project Members, 2001; Kaufman et al., 2004; Smol et al., 2005; Briner et al., 2006; Michelutti et al., 2007; Thomas et al., 2008; Axford et al., 2009a). The Northeastern coastal lowlands of Baffin Island were likely ice free by approximately 14 ka BP (Miller et al., 1977, 2005; Briner et al., 2007a) as evidenced by cosmogenic exposure dating of glacially deposited erratics (Miller et al., 2005). However, the interior of Baffin Island, as well as some fiord regions, may have remained ice covered until 8 ka BP to 7 ka BP (Miller et al., 2005; Wolfe and Smith, 2004; Anderson et al., 2008). Following the widespread deglaciation of Baffin Island, initial post-glacial temperatures on eastern Baffin Island and adjacent Baffin Bay were cooler than present, although reconstructed maximum temperatures [i.e. the Holocene thermal maximum (HTM)] typically occur in the first few millennia of this epoch (e.g. Levac et al., 2001; Kerwin et al., 2004; Briner et al., 2006; Axford et al., 2009a).

On the Clyde Foreland on northeastern Baffin Island (Fig. 1), a regionally well-defined warm period from 10 ka BP to 8.5 ka BP has been identified, with temperatures ~5 °C warmer than modern summer conditions (Briner et al., 2006). The NorthGRIP Greenland ice core oxygen isotope record indicates regional climate variability for the first 1.5 ka of the Holocene epoch, with a distinct cold event at 8.2 ka BP (Johnsen et al., 2001). Similarly, abrupt cold reversals during the early-Holocene warming trend have been indicated by the remains of chironomid (non-biting midges) assemblages preserved in lake sediments from the Clyde Foreland (Axford et al., 2009a), as well as by additional proxies of whole-lake production (Briner et al., 2006).

Pollen-based paleoclimatic research identifies a warm period from ~6 to 3 ka BP across most of North America (Viau et al., 2006). On Baffin Island, a regional climatic optimum has also been defined in the early- to mid-Holocene (e.g. Levac et al., 2001) from ~6.8 to 5.7 ka BP, which likely extended until ~3 ka BP (Williams and Bradley, 1985), although a palynological perspective indicates cooling from ~5.7 to 4.5 ka BP (Short et al., 1985). Palynological studies indicate the Clyde River region experienced temperatures ~1 °C warmer than present by 6 ka BP (Kerwin et al., 2004). Neoglacial cooling across Baffin Island began at ~7 to 6 ka BP in the mid-Holocene (e.g. Briner et al., 2006), with intensified cooling following ~3.6 to 2.5 ka BP (Levac et al., 2001; Wolfe, 2003; Kerwin et al., 2004; Miller et al., 2005), although Miller et al. (1977) suggested that the oldest Neoglacial moraines date at 3.2 ka BP. Neoglaciation led into the Little Ice Age spanning ~1450 to 1850 AD, which is regionally (e.g. Johnsen et al., 2001; Podritske and

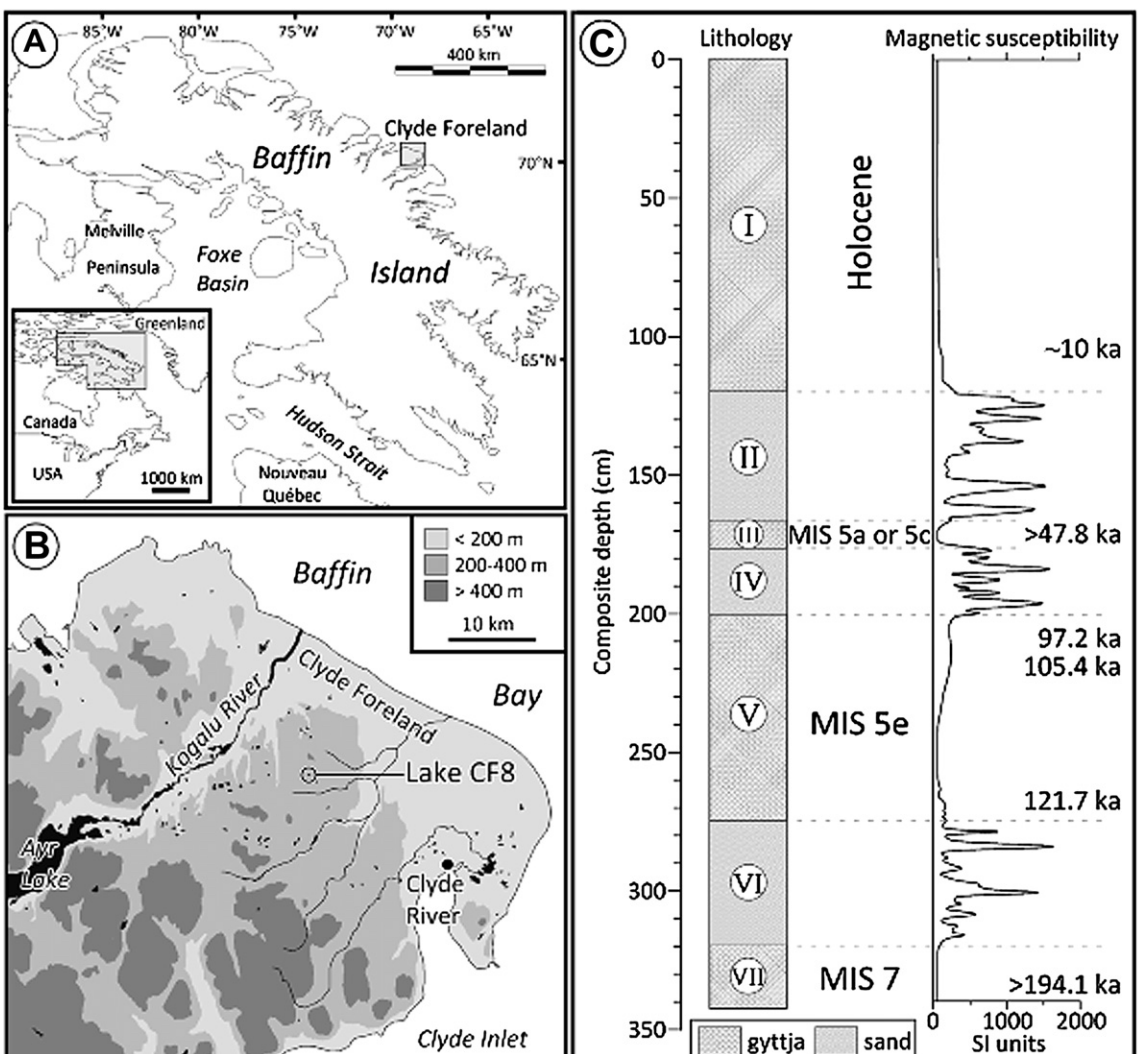

Fig. 1. Location of the Clyde Foreland on Baffin Island (A) and of Lake CF8 (B). The composite stratigraphy of sediment cores from Lake CF8 (C) is shown alongside magnetic susceptibility and approximate ages for the various lithological units. Additional details are provided in Briner et al. (2007b) and Axford et al. (2009a,b).

Gajewski, 2007) and across Baffin Island (e.g. Moore et al., 2001), with minimum temperatures at ~350 yr BP (Williams and Bradley, 1985).

Eastern Baffin Island was pervasively glaciated during the Late Quaternary and remains a largely glacial landscape (Andrews, 1989) and thus few sedimentary records extend beyond Holocene age. This is common across all glaciated landscapes, however a few paleoenvironmental records that extend through glacial cycles have been discovered. For example, relict landscapes from beneath continental glaciers have been identified from within the limits of the Laurentide Ice Sheet (LIS; e.g. Briner et al., 2005), the Fennoscandian ice sheet (e.g. Stroeven et al., 2002), as well as the Antarctic ice sheet (Lewis et al., 2008). Although extremely rare, lake sediment records dating to the last interglacial (i.e., marine isotope stage (MIS) 5, including portions of either substages 5e or 5a, or both) have been recovered from eastern Baffin Island from the Cumberland Peninsula (Wolfe et al., 2000; Francis et al., 2006; Fréchette et al., 2006) and on Brevoort Island (Miller et al., 1999). Due to their morphostratigraphic position on uplands that were characterized locally by cold-based glaciation, these lakes contain sediments that survived being excavated by the LIS.

A number of lake sediment records from eastern Baffin Island that extend to MIS 5 have been investigated, revealing the ecological character of MIS 5 pollen (Miller et al., 1999; Fréchette et al., 2006), diatom (Wolfe et al., 2000) and chironomid (Francis et al., 2006) assemblages in relation to their Holocene counterparts. Miller et al. (1999) used lake sediments from Baffin Island, dated at ~85 ka BP, to identify periods when MIS 5 summer temperatures were as warm, or warmer, than those inferred during the Holocene. Fréchette et al. (2006) showed that the low-Arctic vegetation zone shifted farther north during MIS 5 than at any time during the Holocene. They also concluded that July air temperatures during MIS 5 were a minimum of 4–5 °C higher than present on eastern Baffin Island based on vegetation structural types and significantly higher pollen concentrations relative to the Holocene (e.g. Wolfe et al., 2000; Fréchette et al., 2006). This is in general agreement with chironomid-inferred summer temperatures that record MIS 5 temperatures ~8 °C higher than present-day (Francis et al., 2006; Axford et al., 2011). Late MIS 5 climatic conditions on Baffin Island deteriorated, indicated by declines in low-Arctic vegetation pollen (Miller et al., 1999) and a lack of lacustrine sedimentation between MIS 5 and the Holocene (Francis et al., 2006). However, periods of glacial advance and retreat occurred throughout the Late Wisconsinan (the most recent glacial cycle). For example, Steig et al. (1998) identified an organic layer of lake sediments between inorganic layers, implying a prolonged period of enhanced limnological activity prior to 35 ka BP.

More recently, a lake has been discovered on the Clyde Foreland (Fig. 1), informally referred to as Lake CF8, which preserves an even older sediment sequence that penetrates MIS 7 (Briner et al., 2007b). This record is important because it predates the oldest interpretable Greenland ice core by ~75 ka (NGRIP, 2004), thus offering considerable potential for extending the continental paleoclimate record of the Baffin Bay region. Moreover, because this site is a relatively softwater lake, as opposed to most of the more alkaline lakes in the Arctic (e.g. Douglas et al., 1994), the record may be more responsive to edaphic and climatic changes and thus the nature and magnitude of past diatom assemblage changes are likely different from more alkaline systems (e.g. Michelutti et al., 2006). Although a provisional and abbreviated paleoenvironmental synthesis of this site has already been presented (Axford et al., 2009b), it did not provide the full details of the diatom stratigraphy and the accompanying sediment geochemical record, which are the subjects of the present contribution. We examine and compare the diatom and geochemical records from Lake CF8 to explore similarities and differences between lake ontogenetic trajectories over three successive interglaciations, evaluate the role of paleoclimate and catchment processes in modulating these patterns, and consider explicitly the position of the 20th century in the context of the warmest climatic intervals of the last ~200 ka.

2. Study site

Lake CF8 (unofficial name; 70° 33.42′ N, 68° 57.12′ W, 195 m asl) is situated 17 km northwest of the hamlet of Clyde River on eastern Baffin Island, Nunavut, Canada (Fig. 1). Regional bedrock is comprised of Precambrian granite and gneiss, draped by a range of Quaternary sediments. During the Quaternary, the Clyde River Foreland was repeatedly glaciated by the northeastern margin of the LIS. Previous research has demonstrated that this overriding ice was cold-based and non-erosive (Briner et al., 2005, 2006). The most recent deglaciation, revealed by cosmogenic exposure dating of erratics, terminated at approximately 12 ka BP (Briner et al., 2005). The presence of non-erosive ice resulted in little to no sub-glacial erosion, and the regional preservation of landscape features including lake sediments which predate the Last Glacial Maximum (LGM).

Lake CF8 has a surface area of 0.3 km^2 and maximum depth of 10 m. The lake rests within a 1.1 km^2 catchment and is fed primarily by summer snowmelt. Climate normals from 1971–2000 record a mean annual temperature at Clyde River of −12.8 °C, with average positive temperatures from July through September and 233 mm/yr of primarily snow-based precipitation (Environment Canada, 2004). The lake is dilute, largely unbuffered, oligotrophic, and slightly acidic (Table 1), similar to numerous other lakes on the Clyde Foreland (e.g. Michelutti et al., 2005) and other areas of Baffin Island with similar geology (e.g. Miller et al., 1999; Wolfe et al., 2000). Prostrate dwarf-shrub tundra vegetation surrounds the lake, which is generally snow-covered for at least nine months each year (October–June).

3. Methods and materials

3.1. Sediments and chronology

The Lake CF8 sediment record is a composite of several sediment cores, collected over multiple field seasons from 2002 to 2008. The genesis, stratigraphy, and geochronology of the cores have been described previously (e.g. Briner et al., 2007b; Axford et al., 2009b), so only a general summary is provided here. The

Table 1
Surface water chemistry measurements collected from Lake CF8 in May 2006 under full ice cover. (N. Michelutti unpublished data).

TN (μg/L)	327
TDN (μg/L)	316
TP (μg/L)	3.90
TDP (μg/L)	1.40
DOC (mg/L)	0.97
DIC (mg/L)	0.74
Cl (mg/L)	3.74
SO_4^{2-} (mg/L)	0.80
Na (mg/L)	2.13
K (mg/L)	0.29
Ca (mg/L)	0.36
Mg (mg/L)	0.30
Al (mg/L)	0.01
Si (mg/L)	1.07
Conductivity (μS/cm)	18.84
pH	6.26

cores consist of alternating units of organic-rich lake mud (gyttja) and medium- to coarse-grained sand (Fig. 1C). In general, gyttja units reflect lacustrine deposition during interglacial or interstadial conditions. During regional glaciation, the lake was permanently ice covered prohibiting any autochthonous production and resulting in protracted periods of non-deposition (i.e. hiatuses in the sediment record). The sand units accumulated in the lake during deglaciation. Briner et al. (2007b) assigned roman numerals I-VII to each unit, with odd numbered units (I, III, V, and VII) labeling gyttja and even numbered units (II, IV, VI) labeling sands; units are numbered down core (Fig. 1). A detailed model of sedimentation, as well as a lithological description of each unit, is described by Briner et al. (2007b). The cores used in this study include two surface cores with intact sediment-water interfaces (05-CF8-SC and 08-CF8-SC) and four percussion-piston cores (02-CF8-01, 06-CF8-P1, 04-CF8-02, and 05-CF8-01).

An age-depth model for surface sediments was constructed using excess ^{210}Pb activities coupled to accelerator mass spectrometry (AMS) ^{14}C ages on aquatic bryophytes, which are demonstrably equilibrated with atmospheric $^{14}CO_2$ in Arctic lakes within granitic basins (Wolfe et al., 2004). Ages have been assigned to older sediments using a combination of ^{14}C and optically stimulated luminescence (OSL) dating (Fig. 1C; Briner et al., 2007b). The age-depth models employed here are the same as those in Thomas et al. (2008) and Axford et al. (2009b).

3.2. Diatom analysis diatom-inferred pH reconstruction

Sediment subsamples were prepared for diatom slides following standard procedures for siliceous microfossils (Battarbee et al., 2001). At least 200 diatom valves were identified and enumerated for each interval. Diatom identifications were carried out to the lowest possible taxonomic level (species and subspecies/variety), and taxonomy primarily followed standard floras (Krammer and Lange-Bertalot, 1986, 1988, 1991a,b) in consultation with previous ecological efforts on the Baffin Island flora (e.g. Joynt and Wolfe, 2001; Michelutti et al., 2007). A diatom-inferred pH (DI-pH) transfer function ($r^2_{boot} = 0.44$, $p < 0.01$, $RMSE_{boot} = 0.34$) developed by Joynt and Wolfe (2001) from 61 Baffin Island lakes was used to reconstruct lakewater pH through each interglacial. The pH transfer function was generated using C2 (v 1.4.3; Juggins, 2003) using weighted-averaging regression and calibrations with bootstrapping and classical deshrinking.

3.3. Inorganic and organic sediment geochemistry

To explore the geochemical history preserved within CF8 sediment, we analyzed the concentration of 13 elements including: base cations (Ca, Mg, K, Na), metals (Al, Ti, Mn, Fe, Cu, Zn, Hg, Pb), and nonmetals (P, As). Elements were extracted using 1 M HNO_3 overnight; a standard extractive method for lake sediments (Graney et al., 1995), and were subsequently quantified using a Perkin Elmer Elan 6000 quadrupole inductively coupled plasma mass spectrometer (ICP-MS) at the University of Alberta, Radiogenic Isotope Facility. Total [Hg] was determined using a DMA80 direct mercury at the University of Connecticut, Department of Marine Sciences. Duplicates were run every 10th sample and were consistently within 10% of each other.

Sediment organic matter was analyzed for total carbon (C) and nitrogen (N) by pyrolysis, and total oxidizable organic matter using the loss on ignition method (LOI) (Dean, 1974). The organic C and N content of lake sediments reflects the balance between aquatic and terrestrial production, efficacy of deposition, preservation of organic matter and relationships to both the quantity and quality of inorganic sediment components. Total C and N were measured using a PDZEuropa ANCA-GSL elemental analyzer; C/N is expressed as a molar ratio. The %LOI of sediments was measured at 550 °C (Heiri et al., 2001) and is reported as percent mass loss relative to dry sediment.

3.4. Multivariate data analyses

The major directions of variability in the diatom and biogeochemical data were summarized by two indirect ordinations: Detrended Correspondence Analysis (DCA) for the diatom data and Principal Components Analysis (PCA) for the biogeochemical data. Ordination of the diatom data revealed a gradient length of 3.26 standard deviation units, mandating the use of unimodal DCA ordination; a PCA was used for the geochemical data because there is no *a priori* basis to suspect unimodal (Gaussian) responses. The diatom-based DCA analysis included the relative frequencies of all diatom taxa >1% in any one interval, resulting in the inclusion of 22 taxa from 239 samples. For the PCA, we omitted %C and %N but included the C/N stoichiometric ratio and %LOI analyzed alongside the concentration data for the 16 elements. Due to differences in units, these data were first standardized to normalize variances, and PCA was conducted on a centered correlation matrix. To illustrate the main trajectories and potential drivers of limnological development through each interglacial period, a third summary ordination (PCA) was run incorporating a combined subset of both biological (i.e. diatoms) and geochemical proxies. These proxies included key diatom genera (small colonial Fragilariaceae, *Eunotia* taxa, and *Aulacoseira* taxa) as well as the sum of all base cations (Ca^{2+}, Mg^{2+}, K^+, Na^+), C/N (molar), LOI, and Hg. Diatom-inferred pH and midge-inferred July air temperature (Axford et al., 2009b) were included as passive variables to explore the relationships between climate, biology, lake-catchment interactions, alkalinity and organic matter. All ordinations were performed using CANOCO version 4.5 (ter Braak and Šmilauer, 2002). To provide some information on the analogue situation of the diatom-based pH inferences, a Canonical Correspondence Analysis (CCA) was run using the environmental variables and modern samples with the fossil samples plotted passively.

4. Results

4.1. Diatom flora

A total of 123 diatom species, from 36 genera, were identified in the CF8 sediment record (Wilson, 2009). Scanning electron and light micrographs of the dominant diatom taxa are shown in Fig. 2. The flora is consistent with previous investigations from Baffin Island (Wolfe, 1996a; Joynt and Wolfe, 2001). Relative frequencies of the dominant taxa are displayed stratigraphically alongside DI-pH in Fig. 3. Below we provide details on the assemblage data for each interglacial period as well as the MIS 5a interstadial.

4.1.1. Unit I – Holocene (MIS 1)

The CF8 lake sediment Holocene record begins at approximately 12 ka BP (where BP = 1950 AD), which corresponds to the earliest appearance of postglacial diatoms. A surface gravity core with an intact sediment-water interface captures the most recent history and is presented as a separate unit (uppermost panel Fig. 3). Age-depth relationships developed using excess ^{210}Pb activities and ^{14}C ages indicate there is significant overlap between the two cores (Thomas et al., 2008; Axford et al., 2009b).

Shortly after glacial retreat and until approximately 8.7 ka, the diatom flora is dominated by small benthic Fragilariaceae composed primarily of *Fragilariforma exiguiformis*, and a short-

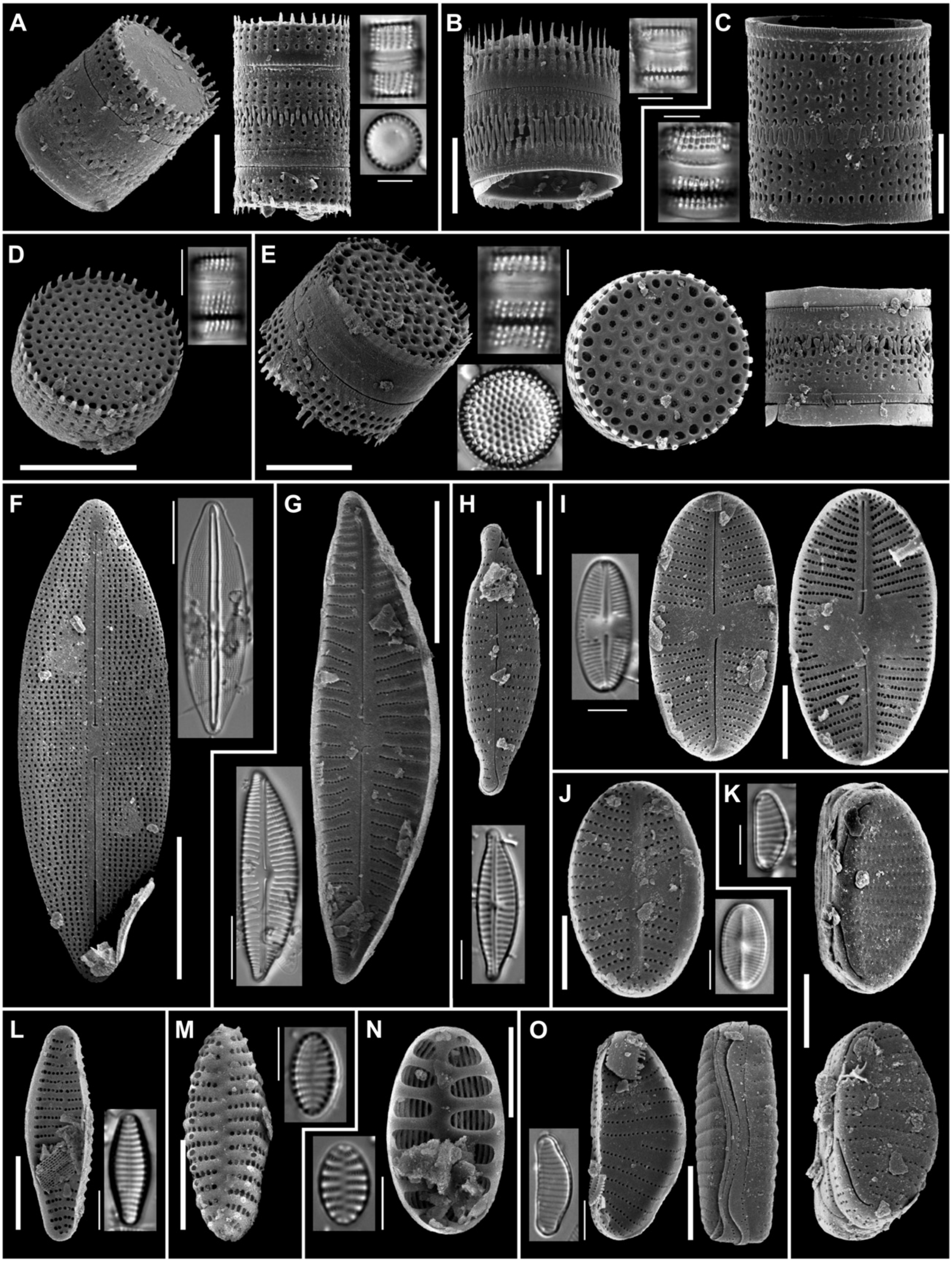

Fig. 2. Images of selected subfossil diatom taxa from H_2O_2–digested sediments of Lake CF8, illustrated pairwise in scanning electron microscopy (SEM) and light microscopy (LM). SEM images were obtained using a JEOL-6301F field-emission instrument; whereas a Leica DMRB with differential interference contrast optics was used to capture LM images of Naphrax-mounted specimens viewed under oil immersion. (A) *Aulacoseira alpigena* (Grunow) Krammer; (B) *A. perglabra* (Østrup) Haworth; (C) *A. lirata* (Ehrenberg) Ross; (D) *A. distans* var. *distans* (Ehrenberg) Simonsen; (E) *A. distans* var. *nivalis* (Ehrenberg) Simonsen; (F) *Frustulia rhomboides* var. *crassinervia* (Ehrenberg) De Toni; (G) *Encyonema hebridicum* (Gregory) Grunow ex Cleve; (H) *E. gaeumannii* (Meister) Krammer; (I) *Psammothidium helveticum* var. *minor* (Hustedt) Bukhtiyarova & Round; (J) *Achnanthes curtissima* Carter; (K) small indeterminate *Eunotia* sp.; (L) *Fragilariforma exiguiformis* Bertalot; (M) *Staurosira venter* (Ehrenberg) Grunow in Van Heurck; (N) *Staurosirella pinnata* (Ehrenberg) Williams & Round; and (O) *Eunotia exigua* (Brébisson ex Kiitzing) Rabenhorst. Thick and thin scale bars refer to SEM and LM images, respectively. Scale bars are alternately 10 μm (A–G) and 5 μm (H–O).

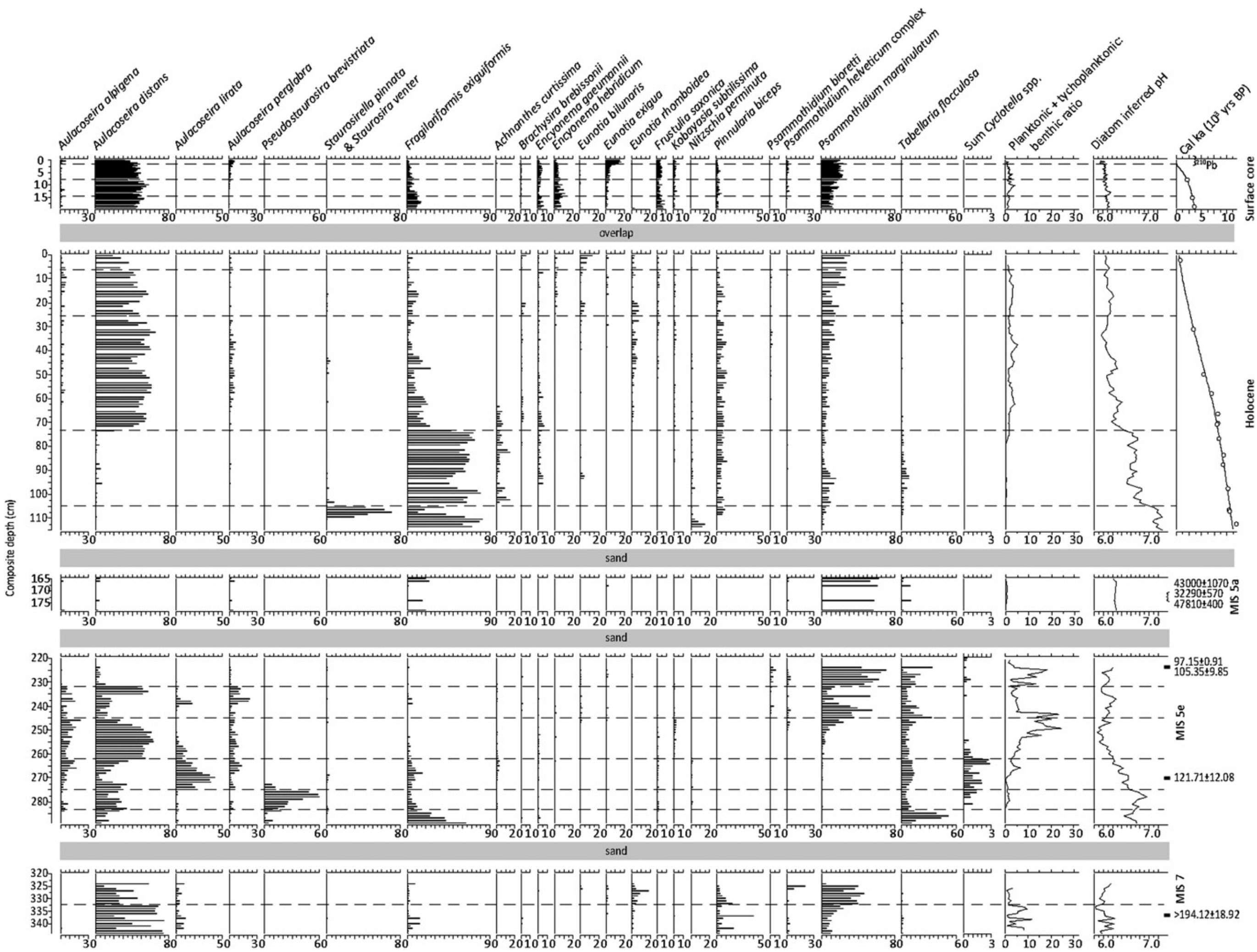

Fig. 3. Summary diatom stratigraphy showing relative abundances (dominant taxa only, i.e. those >10% relative abundance), diatom-inferred pH, and age model for the CF8 composite sediment sequence. Major diatom zones (dashed lines) were created using constrained incremental sum of squares (CONISS) cluster analysis in the program TILIA (ver. 2.0.b.4; Grimm, 1993). Note the x-axis scale change for *Cyclotella* spp. (*sensu lato*).

lived peak in *Staurosirella pinnata* and *Staurosira venter* (Fig. 3). Also present at this time, although in smaller abundances, are several benthic taxa including *Nitzschia perminuta*, *Navicula digitulus*, *Cavinula variostriata*, *Pinnularia biceps*, and *Psammothidium marginulatum*.

After ~8.7 ka BP there is a rapid shift in dominance from small benthic Fragilariaceae to tychoplanktonic *Aulacoseira* taxa, mainly *A. distans*, with lesser amounts of *A. alpigena* and *A. perglabra* (Fig. 3). The continued dominance of the *A. distans* throughout cool periods such as the onset of Neoglacial conditions and Little Ice Age (LIA) suggests that the open water period during these times was sufficient in length to establish large populations of this and other tychoplanktonic *Aulacoseira* taxa. The switch in dominance from Fragilariaceae to *Aulacoseira* taxa is most likely related to a decrease in lakewater pH (Joynt and Wolfe, 2001), due to reduced terrigenous inputs and climate-driven pH dynamics (Michelutti et al., 2006). The most recently deposited sediments (i.e. 20th century) contain unprecedented abundances of *Eunotia exigua* which was only present infrequently (<5%) elsewhere in the sediment record (Fig. 3).

4.1.2. Unit III – MIS 5a

This thin, moss-rich section of core is correlated with interstadial conditions following peak warmth of the last interglacial and was likely deposited during MIS 5a (Briner et al., 2007b). Diatom analysis was not performed on all consecutive intervals from this sequence; however, in all intervals examined, the dominant taxon was *Psammothidium marginulatum*, which composed at least 50% of the relative abundance. The dominance of the periphytic *P. marginulatum* is consistent with the abundant moss fragments found in this section of the core, which have been identified as *Warnstorfia exannulata*, an extant taxon to many Baffin Island lakes that commonly forms horizons in sediment cores (Wolfe, 1996a; Miller et al., 1999). *Warnstorfia exannulata* often grows submerged, suggesting an expanded littoral zone within CF8 during this time. *Fragilariforma exiguiformis* was also consistently present at approximately 20% relative abundance (Fig. 3). Although not shown in Fig. 3, *Stauroneis anceps*, a circumneutral, benthic diatom (Van Dam et al., 1994) reaches a maximum abundance of 17% and is noteworthy in that it is only found in this section of the entire Lake CF8 sediment record.

4.1.3. Unit V – MIS 5e

The OSL ages on this section of the core constrain its deposition to the last interglacial *sensu stricto* (MIS 5e) (Briner et al., 2007b). Diatom assemblages in MIS 5e follow largely similar ontogenetic trends to those in the Holocene but with some differences. Similar to the early Holocene, the initial postglacial assemblage in the MIS

5e is dominated by *F. exiguiformis*, which suggests a resetting of limnological conditions during deglaciation (Fig. 3). As *F. exiguiformis* declines in abundance there is a concomitant rise is *Pseudostaurosira brevistriata*, another small, benthic fragilarioid.

Similar to the mid-to-late Holocene, the dominance of small colonial Fragilariaceae taxa is superceded by *Aulacoseira* taxa including *A. distans*, as well as *A. alpigena*, *A. lirata*, and *A. perglabra*. Of particular note is *A. lirata*, which is one of the most heavily-silicified taxa occurring in Baffin Island lakes and thus requires wind-induced turbulent conditions to maintain its position in the water column. Its presence may be indicative of warmer and wetter summer seasons that supplied greater concentrations of silica to the lake and allowed more turbulence (Miller et al., 1999). In support of this hypothesis, we recorded appreciable relative abundances of the tychoplanktonic, *Tabellaria flocculosa* and perhaps most noteworthy, the presence of *Puncticulata bodanica*, which only occurs during MIS 5e and is the only truly planktonic taxon of the entire CF8 record (Fig. 3).

During the end of the MIS 5e, *P. marginulatum* increases in abundance at the expense of *Aulacoseira* taxa, which again is similar to the pattern of diatom succession recorded in the late Holocene (Fig. 3). As regional climate descended into the penultimate glaciation at the end of the MIS 5e, Lake CF8 likely became increasingly ice covered, which is reflected in the decreasing abundances of diatom taxa in this portion of the sediment core.

4.1.4. Unit VII – MIS 7

This lowest-most organic unit is older than 194 ka BP (Fig. 1), and is ascribed to the penultimate interglacial (MIS 7; Briner et al., 2007b). The core section of MIS 7 from Lake CF8 is not complete, but it does capture a portion of full interglacial conditions, albeit the waning stages. Similar to the late stages of MIS 5e and the Holocene, *A. distans* is the dominant taxon, with *P. marginulatum* showing a trend of increasing abundance over time (Fig. 3). Benthic taxa also present in low abundances at this time include *Fragilariforma exiguiformis*, *Pinnularia biceps* and *Neidium* and *Frustulia* taxa. In addition, while only a qualitative observation, the sediments of MIS 7 contained far fewer diatom valves compared to the subsequent two interglacial periods, perhaps indicating less overall production. Planktonic to benthic diatom ratios were similar to late-MIS 5e (Fig. 3).

4.1.5. Diatom-inferred pH reconstructions

Diatom-inferred pH (DI-pH) reconstructions for each full interglacial period (ie, the Holocene and MIS 5e) show similar trajectories over time (Fig. 3). A CCA with the modern diatom samples and environmental variables from Joynt and Wolfe (2001) with CF8 fossil samples plotted passively shows that the fossil samples generally plot within the outline of the modern samples suggesting relatively good analog matching for most sediment intervals (Fig. 4). Following the initial retreat of the cold-based ice, lakewater pH levels are at their highest values. In the Holocene, initial DI-pH values are slightly basic, whereas in MIS 5e, DI-pH values are slightly acidic. In both the Holocene and MIS 5e, DI-pH values show a progressive decline over time until eventually stabilizing at approximately pH 6. Correlations between downcore DI-pH and DCA axis 1 species scores suggest that pH is a dominant ecological gradient governing diatom species composition in Lake CF8 ($r = 0.73$ for surface sediments; $r = 0.96$ for Holocene; $r = 0.81$ for MIS 5e; $r = 0.35$ for MIS 7), a finding that has been documented in

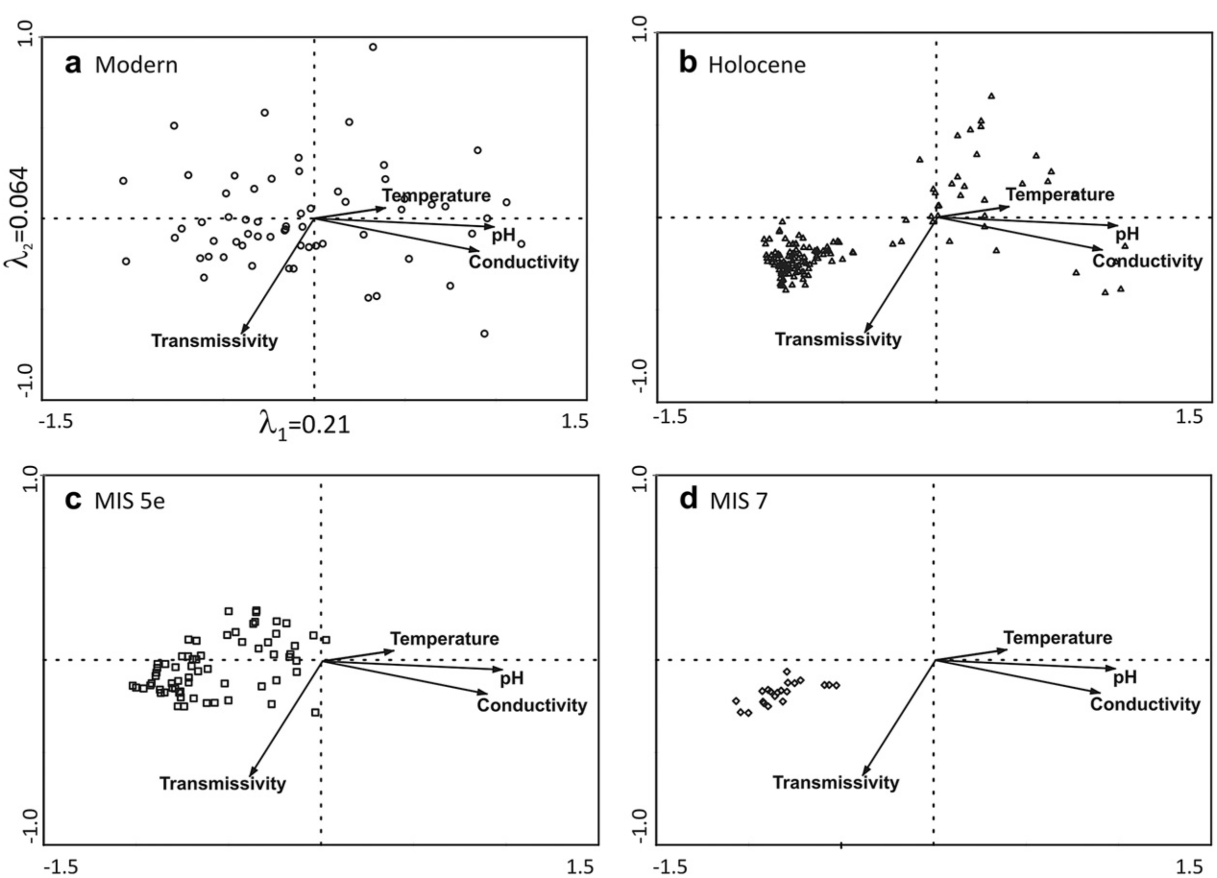

Fig. 4. CCA of modern diatom samples (a) and significant environmental variables from the Baffin Island training set of Joynt and Wolfe (2001) with the CF8 fossil samples plotted passively showing the Holocene (b), MIS 5e (c) and MIS 7 (d).

several Baffin Island lakes (Wolfe, 2003; Michelutti et al., 2007). The modern pH of Lake CF8 is approximately 6.3, which is in agreement with the DI-pH of 6.0 in the uppermost sediments.

4.2. Sediment geochemistry

4.2.1. Unit I – Holocene

The results of the inorganic and organic sediment geochemistry are presented stratigraphically in Fig. 5. Many of the elements measured exhibit similar stratigraphic profiles. In general, the concentrations of base cations, metals, and nonmetals all exhibit low values immediately following deglaciation and subsequent increases during the early Holocene. Peak concentrations are reached during the early Holocene. After ~8 ka BP (80–90 cm), elements either remain stable (%C, %N, LOI, Zn, Pb, Na, As, Cu, Al, Hg) or display subtle declines (P, Mn, K, Mg, Ti, Fe, Ca) through the Neoglacial. The C/N ratio closely tracks that of %C.

The most recent sediments are characterized by relatively stable elemental profiles, which remain within the range of Holocene variability. This includes metals that are commonly associated with anthropogenic pollution, although as Michelutti et al. (2009) have described, concentration data do not necessarily reflect the rate of metal loadings because of recent increases in the rate of lake sedimentation. Indeed, independently measured stable Pb isotope ratios ($^{206}Pb/^{207}Pb$) measured on recent sediment in CF8 register a steadily increasing influx of anthropogenic Pb, despite unchanging total Pb concentrations (Michelutti et al. 2009).

4.2.2. Unit V – MIS 5e

Most elements display considerably less stratigraphic variability in MIS 5 compared with the Holocene (Fig. 5). Organic matter content recorded in MIS 5e sediment is about half of the mean Holocene content. In contrast, many of the base cations, metals, and nonmetals exhibit concentrations that are of similar magnitude to Holocene concentrations. While our sampling resolution for the MIS 5e is lower than for the Holocene, there is a notable lack of any early last interglacial increase in both organic matter and elemental concentrations. The C/N ratio remains stable at ~13 for the first half of MIS 5e, but abruptly increases to ~18 at 245 cm depth. This depth also marks a gradual but steady increase in the magnetic susceptibility (Fig. 1C), and a subtle increase in some of the lithogenic elements measured (P, Mn, Mg, Ti, Fe, Ca, Al). These parallel trends suggest an increase in the delivery of allochthonous materials from the catchment to the lake during the latter half of MIS 5e.

4.2.3. Unit VII – MIS 7

In general, elemental concentrations within MIS 7 sediment are comparable to those seen during MIS 5e (Fig. 5). However, as noticed within the Holocene and MIS 5e, organic matter content (%C and %LOI) decreases again by about one-half. Three of the four base cations (K, Mg, Na) and a number of the other elements (Mn, Ti, Fe, Al, and to a lesser extent Zn) display two prominent peaks in concentration late in MIS 7. In the case of Mn, K, Mg, and Ti these peaks exceed maximum concentrations during within both last interglacial and Holocene sediments. The C/N ratio remains >11 during the latter portion of MIS 7.

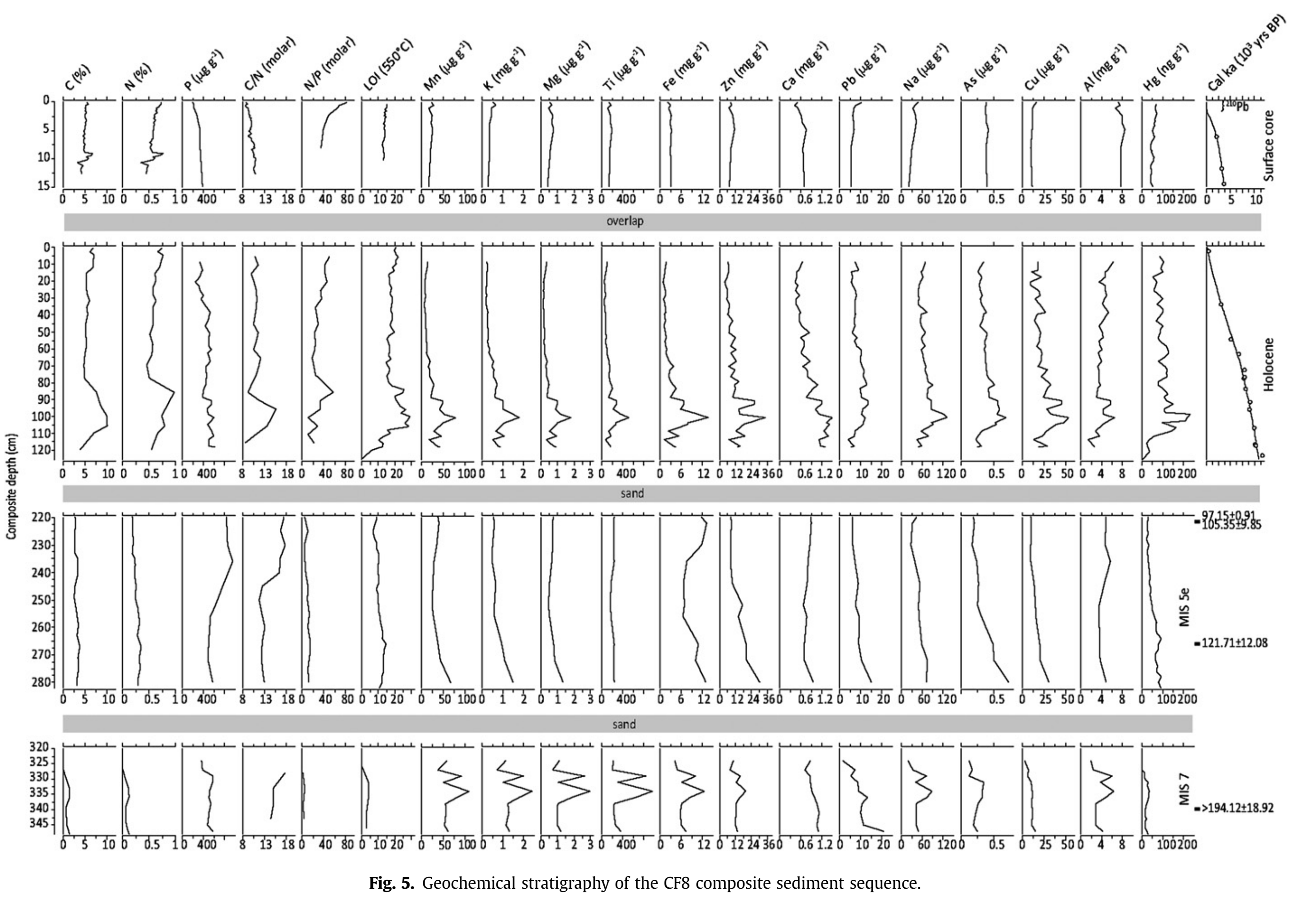

Fig. 5. Geochemical stratigraphy of the CF8 composite sediment sequence.

4.3. Ordination results

The results of the DCA and PCA ordination analyses, on the diatom and geochemical data, respectively, are shown in Fig. 6. Axis 1 of the DCA, which explains 16.0% of variance in the diatom data, displays the same decreasing trends through both the Holocene and MIS 5e. In addition, axis 1 scores from the latter portion of MIS 7 are comparable to those recorded during the late MIS 5e and late Holocene, suggesting a similar overall diatom trajectory. In contrast, DCA axis 1 scores from the most recent sediments progressively decline. This decrease in the diatom DCA is driven primarily by the appearance of taxa (e.g. *E. exigua*; Fig. 6B) which were present in only trace amounts over the past ~200,000 years.

A PCA biplot summarizes the major trends across key biological and geochemical data for all three interglacial periods (Fig. 7). The variables used for the PCA include geochemical data (LOI, Hg, C/N ratios, and the sum of base cation concentrations [Σ Ca, Mg, K, Na]) and biological data (Σ small colonial Fragilariaceae, Σ tychoplanktonic *Aulacoseira* taxa, and Σ *Eunotia* taxa). Chironomid-inferred temperature and DI-pH were run as passive variables and thus did not contribute to the formation of the ordination axes. Axis 1 and 2 explained 39% and 31% of the cumulative variance in the dataset, respectively. Sample scores for each interglacial period are connected together as lines, following chronological order, to show the trajectories of changes through time (Fig. 7). The earliest recorded portions of the Holocene and MIS 5e (denoted as solid circles in Fig. 7) show similar starting points. Note that because the core section from MIS 7 is not complete, its starting point does not reflect the period immediately following deglaciation. The late MIS 5e and MIS 7 show similar end points (denoted by triangles), whereas sample scores from the late Holocene, including the Anthropocene, have followed a trajectory toward unprecedented environmental conditions with respect to the last ~200,000 years of the lake's active history (Fig. 7).

5. Discussion

The Lake CF8 sediment record provides a rare opportunity to compare the biological and geochemical trajectories of an Arctic lake over the last three interglacial periods. These data can be used to place the recent changes of the Anthropocene within the context of the last ~200,000 years of natural climate variability, as well as to examine more fundamental limnological questions such as deciphering the respective roles of climate and catchment variables in driving Arctic lake ontogeny.

5.1. Diatom assemblages of the past three interglacial periods

The composite sediment record from Lake CF8 records broadly repeating patterns of diatom assemblage shifts during each interglacial period, despite intervening full glaciations (Fig. 3). Following each glacial retreat, the lake is colonized by similar pioneering diatom taxa and then follows similar patterns of succession over time. It appears as if diatom assemblages are reset, or "rebooted", following each glacial retreat. In Arctic lakes, diatom assemblages are primarily governed by climate-driven changes in ice cover, which can affect habitat type and availability, as well as a number of attendant limnological variables, such as lakewater pH (Smol and Douglas, 2007; Douglas and Smol, 2010). The repeating pattern of diatom succession over the last three interglacials suggests that climate has also followed a common pattern within each interglacial period. Yet subtle differences among interglacials are clearly evident as well (e.g. the presence of *Cyclotella sensu lato* in MIS 5e sediment) suggesting some degree of ecological uniqueness. Below we discuss the trends in diatom succession for each interglacial period.

5.1.1. The Holocene

The small benthic fragilarioids that dominate the early Holocene are commonly documented as the first colonizers in newly formed or deglaciated lakes, particularly in Arctic regions (Smol, 1983; Pienitz et al., 2004; Douglas and Smol, 2010), and they often flourish in environments with cold water temperatures, prolonged ice cover, and enhanced catchment erosion (Smol, 1983, 1988; Lotter and Bigler, 2000). The pervasiveness of these alkaliphilous fragilarioids in lakes from recently deglaciated environments is commonly attributed to high inputs of alkalinizing base cations from an abundance of freshly deposited glacial till. However, base cation inputs near Lake CF8 would be expected to be minimal due to the non-erosive, cold-based glaciological regime at this location. Indeed, the geochemical data from the early Holocene record base cation (e.g. Ca, K, Mg, Na) profiles that have low initial concentrations followed by short-lived peaks and subsequent declines (Fig. 5). During these fluctuations in base cation concentrations, the relative abundances of the fragilarioid taxa remained relatively constant (Fig. 3), suggesting that the acid base equilibrium of Lake CF8 is governed largely by climate (see section 5.2).

Chironomid-inferred summer water temperatures from Lake CF8 indicated that peak Holocene warmth was reached between 7 and 10.5 ka BP (Axford et al., 2011). Although, the timing of the Holocene thermal maximum varied spatially and temporally across the Arctic (Kaufman et al., 2004), it is generally accepted that following a climatic optimum, temperatures began to progressively cool due to declining insolation. The diatom record suggests that the onset of Holocene cooling at Lake CF8 occurred ~8.7 ka BP, with a switch in dominance from alkaliphilous fragilarioids to the acidophilous *Aulacoseira* taxa, including *A. alpigena* (Grunow) Krammer, *A. distans* (Ehrenb.) Simonsen, *A. lirata* (Ehrenberg) Kützing, and *A. perglabra* (Østrup) E. Y. Haw. (Fig. 3). The change in lakewater pH would have occurred as a result of prolonged ice cover, which limits photosynthesis and traps respired CO_2 within the water column. Similar patterns of diatom assemblage shifts (i.e. a change in dominance from an alkaliphilous to an acidophilous assemblage) have been documented in lakes elsewhere on Baffin Island (Wolfe and Härtling, 1996; Miller et al., 1999; Wolfe et al., 2000; Michelutti et al., 2007). The cooling, and subsequent pH decline, recorded at Lake CF8 might have been related to catastrophic drainage of proglacial Lake Agassiz at ~8.5 ka BP and the subsequent rerouting of the cold Laurentide Ice Sheet meltwaters from the St Lawrence River to the Hudson Bay and Strait (Teller and Leverington, 2004).

5.1.2. The interstadial (MIS 5a)

This unit of organic sedimentation may be conceptually regarded as a cold analogue, as an interstadial period reflects colder temperatures than an interglacial with attendant terrestrial and limnological responses. Similar sediments of pre-Holocene age have been recovered elsewhere on Baffin Island, and share many characteristics with the CF8 record. For example, a gyttja unit with abundant moss fragments, dated at ~43.1 ka BP, was recovered from Robinson Lake (63°23.8′N; 64°15.7′W) on southeastern Baffin Island (Miller et al., 1999). The gyttja unit from Robinson Lake contained sparse pollen, which may indicate that it was deposited at a time when the regional climate was cold and still partially glaciated, limiting the establishment of local vegetation. Also at Fog Lake (67° 11′N, 63° 15′W) on the north coast of the Cumberland Peninsula on Baffin Island, pre-Holocene aged sediment attributed to interstadial stages contained moss-rich units dominated by *P. marginulatum* (Wolfe et al., 2000). The diatom *P. marginulatum* reaches its highest abundances in the Lake CF8 record in the late stages of an interglacial (e.g. MIS 5e, MIS 7; Fig. 3) just prior to the onset of full glacial conditions.

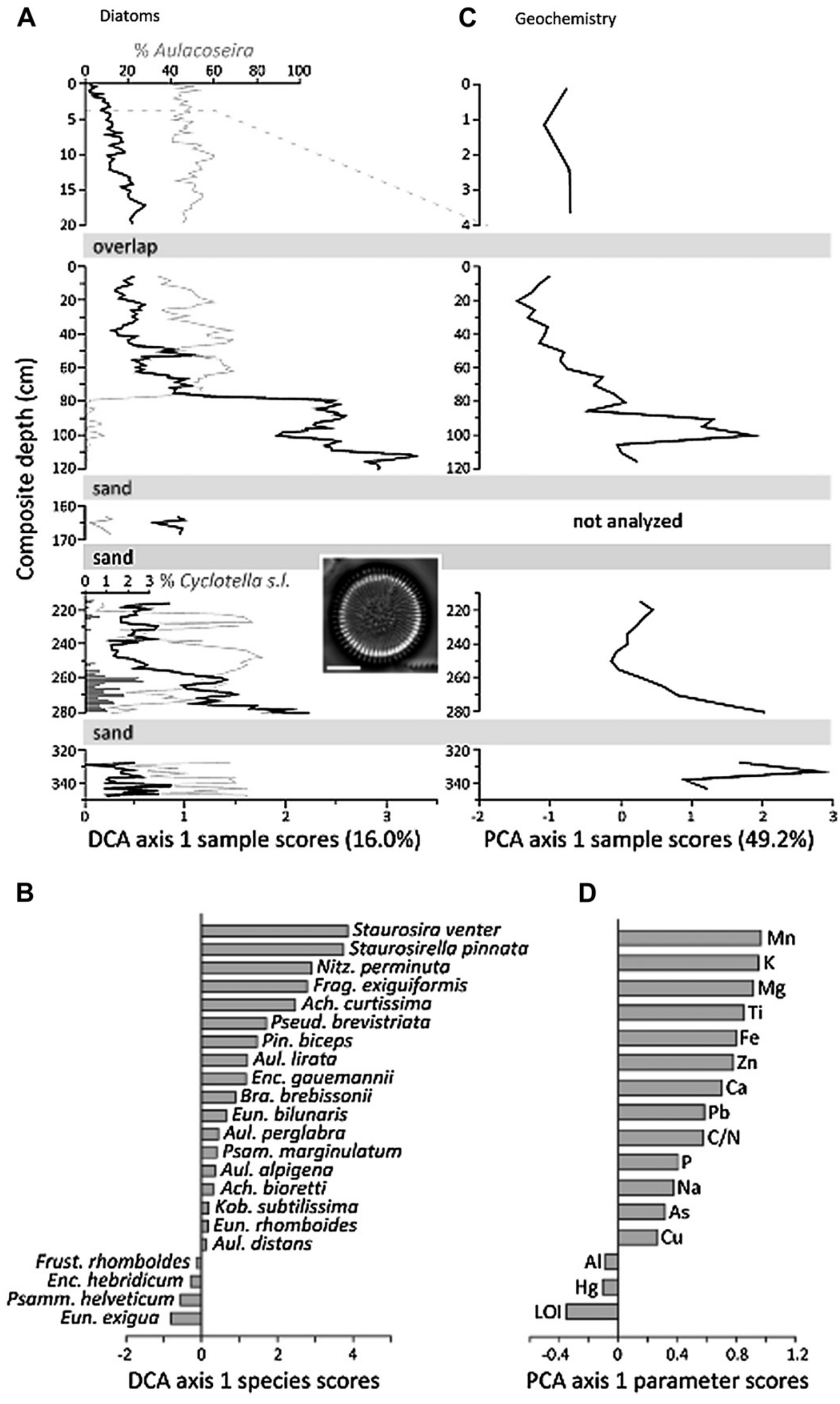

Fig. 6. Leading axis ordination results plotted stratigraphically (sample scores) with scores for the included parameters shown below. Two separate ordinations were conducted: DCA of dominant diatoms (A, B) and PCA of assorted geochemical data (C, D). For diatoms, the summed percentages of the genera *Cyclotella* (*sensu lato*) and *Aulacoseira* are also shown. The inset photomicrograph in panel (A) is a sample cyclotelloid diatom, *Puncticulata* cf. *comta* (Ehr.) Håkansson (scale bar shown equals 5 μm), from CF8, MIS5e sediments.

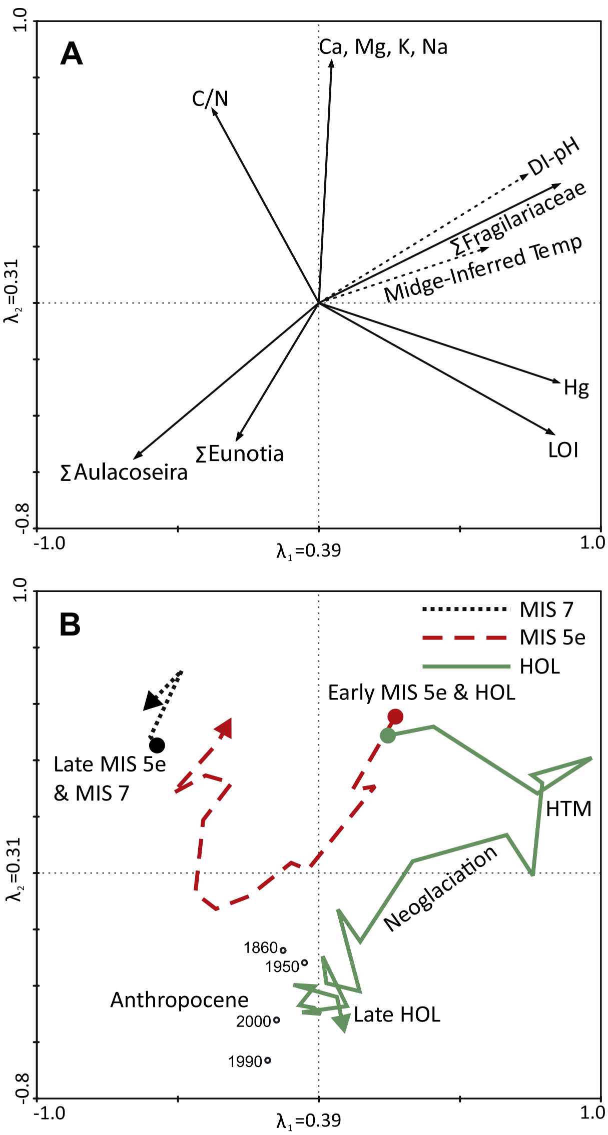

Fig. 7. Paleolimnological synthesis of the CF8 record using PCA of integrated diatom and geochemical data. (A) Parameter loadings on the first two axes; passive variables are dashed arrows. (B) Evolution of sample scores in the same ordination space. See text for details.

5.1.3. The Last Interglacial (MIS 5e)

The climate of MIS 5e was likely more unstable (GRIP Members, 1993) and warmer than any time during the Holocene on Baffin Island and elsewhere in the Arctic (de Vernal et al., 1991), as reconstructed from multiple lines of evidence including past sea level (CAPE Project Members, 2001), elevated pollen concentrations in lake sediment cores (e.g. Miller et al., 1999; Wolfe et al., 2000; Kerwin et al., 2004), the presence of marine molluscs in terrestrial records (e.g. Miller et al., 1977), and chironomid-inferred July temperatures (Francis et al., 2006; Axford et al., 2011). In addition, the lengths of the individual summer seasons were likely longer than those of the Holocene (e.g. Miller et al., 1977; Fréchette et al., 2008). The warmer climate during MIS 5e compared to the Holocene may explain some of the differences in the diatom assemblages between these two interglacial periods. For example, during MIS 5e, a greater diversity of planktonic species developed, including *Aulacoseira lirata* that appears only in MIS 5e at any significant abundance (Fig. 3) and requires turbulent, open water. Also, MIS 5e is the only period in the entire Lake CF8 sediment core that records a truly planktonic taxa in *Cyclotella bodanica* (Fig. 6), indicating extended periods of open water conditions. Furthermore, several periphytic species that appear in the Holocene constitute larger abundances in MIS 5e, which may indicate greater periphytic habitat availability (Fig. 3). Glaciochemical data suggest that MIS 5e was about 5 °C warmer than the Holocene average (NGRIP, 2004), and it has been surmised that this is largely due to the relatively early deglaciation in the summer insolation cycle, allowing for peak insolation at times when much of the eastern Arctic was already deglaciated (CAPE Project Members, 2001).

Several sediment records from elsewhere on Baffin Island have captured MIS 5e sediment sequences. The interglacial gyttja unit from Lake CF8 is likely comparable to the ascribed MIS 5 sediments from both Fog Lake (Wolfe et al., 2000) and Robinson Lake (Miller et al., 1999) on southeastern Baffin Island. The Fog Lake sediment record contains a spike in *Fragilariforma virescens* marking the onset of MIS 5e, similar to the CF8 record, though *Aulacoseira* taxa appear only sporadically (Wolfe et al., 2000). A distinct feature of the Lake CF8 early MIS 5e diatom stratigraphy is the co-occurrence of *F. exiguiformis* and *A. distans* at appreciable abundances, which also occurs in the Fog Lake record (Wolfe et al., 2000) and may indicate that regionally warmer temperatures were already established following deglaciation, perhaps suggesting a faster transition from glacial to interglacial conditions in early MIS 5e compared to the early Holocene. Interestingly, the heavily silicified *A. lirata* also appeared only in the MIS 5 sediments at Fog Lake, which Miller et al. (1999) attribute to intensified silicate weathering from the catchment relative to the Holocene. The similarities between these records indicate that the MIS 5e climate had similar limnological consequences across eastern Baffin Island.

5.1.4. The previous Interglacial (MIS7)

Few records are available pertaining to the climate during MIS 7 (e.g. Desprat et al., 2006). The only other comparable diatom assemblage, from Lake El'gygytgyn in Siberia, similarly recorded high abundances of planktonic species during multiple warm periods of the full MIS 7 interglacial, with persistent but low abundances of benthic and periphytic diatom taxa (Cherapanova et al., 2007). Perhaps the most interesting characteristic of the MIS 7 record from Lake CF8, however, is the similarity of the diatom assemblages and diatom-inferred pH to those of the upper segments of both the Holocene and MIS 5e (Fig.3). The diatom record therefore indicates that a particular pattern of diatom assemblages at this site characterizes the end-stage of an interglacial, implying a similar climatic deterioration into glacial periods.

5.1.5. The Anthropocene

The patterns of interglacial lake ontogeny inferred by the diatom record suggests that the development of Lake CF8 following deglaciation during the past three interglacials followed largely common trajectories. The past two centuries, and in particular the past several decades, however, have witnessed deviations within diatom communities that are not comparable to the upper sediments of either MIS 5e or MIS 7, or anywhere else in the ~200,000 year-old sedimentary sequence (Figs. 3 and 6B). A late-Holocene and Anthropocene chironomid-inferred temperature record from Lake CF8 indicates that within the past ~50 years, unprecedented increases in both summer water temperature and primary productivity have occurred (Thomas et al., 2008). The diatom response within that time period recorded a significant increase in *Eunotia exigua* (Fig. 3). The relationship between a warming climate, leading to less ice cover in the warm months and therefore increasing habitat availability for a wider range of diatom growth strategies, has been found in lakes from the High Arctic (e.g. Smol, 1988; Smol et al., 2005) and Subarctic (e.g. Rühland and Smol, 2005) as well as high altitude sites (e.g. Lotter and Bigler, 2000).

Although *E. exigua* is an acidophilic taxon, its increased relative abundance does not reflect a decline in lakewater pH as it merely replaced other taxa with similar pH optima. *Eunotia exigua* has been linked to aquatic mosses (Patrick and Reimer, 1966), which are predicted to increase with warming, which may explain its recent rise in Lake CF8; however, *E. exigua* has yet to be found in moss samples from Baffin Island lakes (Wolfe, 1996b), and it was also not recorded in a moss-rich sediment core from nearby Lake CF3 (Michelutti et al., 2007). Certainly, the dominance of *E. exigua* in recent sediments reflects a changing and expanding littoral habitat. The uniqueness of the modern diatom assemblage at Lake CF8 may be related to the fact that recent warming has been triggered at a different stage of lake ontogeny than in previous warm intervals, such as the early Holocene and MIS 5e, both of which occurred shortly following deglaciation. Thus, the anthropogenic warming of recent times is presaged by fundamentally different catchment conditions and aquatic biogeochemistry compared to earlier warm periods, as evidenced by the sediment geochemical data (Fig. 5). This may explain the uniqueness of the modern diatom assemblages in relation to prior warm intervals.

Post-industrial acidification from long-range emissions is unlikely to account for any of the recent changes recorded in Lake CF8. The deposition of acidic materials is very low in the Canadian Arctic. For example, mean deposition rates for SO_x and NO_3 at Clyde River are estimated to be $<20\ mg\ m^{-3}\ yr^{-1}$, compared to $\sim 400\ mg\ m^{-3}\ yr^{-1}$ in parts of southern Canada and Europe (AMAP, 2006). As would be predicted given its remote location, lakewater SO_4 concentrations in Lake CF8 and other nearby lakes are considerably lower compared to regions that receive high inputs of acidic materials. For example, in the Adirondack region of New York, an area of documented high acidic precipitation, the mean SO_4 concentration recorded from a sample of 155 lakes was $5.7\ mg\ L^{-1}$, range $= 5.14–6.5\ mg\ L^{-1}$ (Charles, 1991). This is several-fold higher than the SO_4 concentration recorded in Lake CF8 ($<1.2\ mg\ L^{-1}$), and in lakes from the Clyde River region ($1.89 \pm 0.91\ mg\ L^{-1}$, $n = 10$). In addition, SO_4 concentrations recorded from snow collected on the lake surface and in the catchment of Lake CF8 are low (0.41 and $0.35\ mg\ L^{-1}$, respectively) indicating that acid shock from spring runoff is unlikely. Moreover, in nearby Lake CF3, an increase in lake-water pH has been recorded in recent decades (Michelutti et al., 2007), which would not be expected if acidic deposition was a causative factor of change in this region. Even a small increase in the growing season length of Arctic lakes allows for diversified habitat availability (Douglas and Smol, 2010). Therefore, while Baffin Island falls within the region that has shown some of the smallest increases in surface air temperatures annually and seasonally from 1966 to 1995 (Serreze et al., 2000), as well as from 1980 to 1999 and in projections into the future decades (Serreze and Francis, 2006), the biological response at Lake CF8 likely indicates that the length of the ice-free season is increasing. Warmer temperatures and longer growing seasons from this region are wholly supported by independent lines of evidence such as a 50% decrease in the areal extent of ice caps since 1958 on northern Baffin Island (Anderson et al., 2008).

The diatom assemblages in the sediments deposited in the past ~50 years cannot be directly compared to the late portions of either MIS 5e of MIS 7, as the corresponding sediment intervals do not indicate similar lengths of time due to core compaction. However, the increase in *Eunotia* taxa does not appear elsewhere in the record, including in the later stages of the past interglacials, and may be indicative of a new biological regime occurring in this lake. A prolonged present interglacial period due to anthropogenic greenhouse gas emissions has been suggested by Berger and Loutre (2002), and may, in addition to other proxy indicators examined from this lake (Axford et al., 2009b), be indicated by the diatom assemblages at Lake CF8, which are unlike any recorded over the past 200,000 years.

5.2. The roles of climate and catchment succession in driving lake ontogeny

Paleolimnological records offer empirical insight into long-term interactions between lakes and their catchments (Deevey, 1942). Edaphic processes are typically invoked as the primary driver of limnological development in recently deglaciated terrain (e.g. Engstrom et al., 2000). For example, base cation leaching from unweathered glacial till is thought to be an important source of alkalinity in newly deglaciated landscapes (e.g. Renberg, 1990). As regional vegetation and soils develop and base cation reserves become depleted, catchment-supplied nutrients become increasingly important (Engstrom et al., 2000). However, sparse vegetation, limited soil development, and continuous permafrost all serve to isolate Arctic lakes from their catchments and heighten limnological response to climate (Koinig et al., 1998; Wolfe, 2002).

Recently, Michelutti et al. (2007) suggested that climate, through the regulation of within-lake dissolved inorganic carbon (DIC) cycling, is more important than catchment processes in controlling the chemical and biological development of Arctic lakes. However, Michelutti et al. (2007) did not directly measure base cation. The CF8 sediment record presented here offers reconstructions of not only biological responses, but also direct measurements of terrestrial geochemical input spanning multiple interglacials. This affords a unique opportunity to examine Arctic lake ontogeny over the last ~200,000 years, with explicit attention paid to both climate- and catchment-driven processes.

Lakewater pH has been shown to be one of the most important controlling variables regulating diatom assemblages across a suite of Baffin Island lakes (Wolfe, 2002) and essentially every dilute lake globally (Battarbee et al., 2010). Lake CF8 presents consistent declines of DI-pH over time throughout the Holocene, MIS 5e, and MIS 7, suggesting successive rebooting of lake-water pH with the onset of each interglacial period. This rebooting has resulted from early postglacial pedogenic processes (Engstrom et al., 2000), which are themselves mediated by insolation-driven changes in climate (Michelutti et al., 2007).

During the early Holocene, inputs of base cations and other lithogenic elements, which serve as an indicator of erosional input from the watershed, were initially low, but subsequently increase reaching peak concentrations during the HTM (Fig. 5). Coeval increases in Hg and other trace metals indicate a tight coupling between watershed erosion and trace metal enrichment at Lake CF8. In contrast, lakewater pH decreases over this same period (Fig. 3), which is opposite to what would be predicted if detrital base cations were important sources of alkalinity. Terrestrial input subsequently declines and there is little variability in catchment weathering over the remainder of the Holocene (the calculation of elemental accumulation rates does little to change the trends described above). In contrast, pH remains between 6.5 and 6.9 until at least 8 ka BP (72 cm), after which point it steadily declines through the Holocene. Thus, there appears to be little stratigraphic evidence for base-cation regulation of lakewater pH though the Holocene, even during periods of pronounced catchment weathering, such as the HTM.

The absence of a relationship between base cation supply and lakewater pH is maintained during MIS 5e as well as the latter portion of MIS 7. During the earliest portion of MIS 5e, lakewater pH is slightly lower (6.5–7.0) than the earliest Holocene (7.0–7.2). This is despite similar base cation concentrations across the two intervals. Moreover, detrital inputs, including base cations, increased during both late MIS 5e and MIS 7 likely as a result of incipient regional glaciation. Yet these increases appear to have carried little consequence for lakewater pH. Therefore, we conclude that variable base cation supply exerts little influence on the development of lakewater pH at CF8.

In contrast, lakewater pH, benthic diatoms (i.e. fragilarioids), and midge-inferred temperature (Axford et al., 2009a,b) are tightly coupled during the interglacials over the ~200,000-year record (Fig. 3); periods of low planktonic to benthic diatom ratios are characterized by elevated pH (e.g. the HTM and early MIS 5e). These relationships suggest that both summer growing season and benthic habitat play an important role in regulating lakewater conditions within CF8. Periods of warming result in decreased lake-ice cover, which serves to increase within-lake primary production (Wolfe, 2002; Michelutti et al., 2007). During warm periods, CO_2 can be directly exchanged with the atmosphere and consumed through phytoplankton photosynthesis, thereby raising lakewater pH. Alternatively, during cool periods, prolonged ice cover traps expired CO_2, thereby lowering lakewater pH through the production of H_2CO_3. This model of climate-driven limnological development is consistent with diatom records from both Robinson and Fog lakes (Miller et al., 1999; Wolfe et al., 2000), implying that the millennial-scale limnological trajectory outlined here is regionally expressed.

6. Conclusions

Lake CF8 represents a rare example of a lake inside the LIS margin that can provide a detailed paleolimnological record of prior interglacial periods. The sediment core data show that interglacial periods have similar biogeochemical ontogenetic patterns that are reset by glaciations. These predictable courses in postglacial development of catchment processes can be tracked by sedimentary geochemical methods. Biological similarities also exist between interglacials, as tracked by subfossil diatom assemblages, but are somewhat less predictable. Declining lakewater pH, as inferred by diatom assemblages, is a recurrent feature of lake ontogeny throughout each interglacial and is foremost mediated by climate. The apparent decoupling of catchment-related processes in driving lakewater pH at Lake CF8 is likely related to the scarcity of fresh tills due to the cold-based glaciological regime that dominated this region. The development of an ecologically unprecedented diatom assemblage in the 20th century reflects an expanding, and possibly more diverse, littoral habitat zone. The uniqueness of this modern assemblage may be related to a warming that initiated not soon after glacial reset, as in prior warm intervals, but 12 millennia later. We conclude that the ecological responses of Arctic lake diatom assemblages to climate warming are not only sensitive to the physical amplitude and character of the warming in question, but also to the timing of its onset in the ontogenetic sequence of the lake. Our study is the first to chronicle the similarities and differences that exist between successive interglacial lake regimes in the Arctic, and to place the Anthropocene in the context of the last ~200,000 years of natural variability.

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References

AMAP, 2006. Acidifying Pollutants, Arctic Haze, and Acidification in the Arctic. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, xii + 112 pp.

Anderson, R.K., Miller, G.H., Briner, J.P., Lifton, N.A., DeVogel, S.B., 2008. A millennial perspective on Arctic warming from ^{14}C in quartz and plants emerging from beneath ice caps. Geophys. Res. Lett. 35, L01502. doi:10.1029/2007GL032057.

Andrews, J.T., 1989. Quaternary geology of the northeastern Canadian Shield. In: Fulton, R.J. (Ed.), Quaternary Geology of Canada and Greenland, vol. K-1. Geological Society of America, Boulder, CO, pp. 276–301.

Axford, Y., Briner, J.P., Francis, D.R., Miller, G.H., Walker, I.R., Wolfe, A.P., 2011. Chironomids record terrestrial temperature changes throughout Arctic interglacials of the past 200,000 years. Geological Society of America Bulletin 123, 1275–1287.

Axford, Y., Briner, J.P., Miller, G.H., Francis, D.R., 2009a. Paleoecological evidence for abrupt cold reversals during peak Holocene warmth on Baffin Island, Arctic Canada. Quat. Res. 71, 142–149.

Axford, Y., Briner, J.P., Cooke, C.A., Francis, D.R., Michelutti, N., Miller, G.H., Smol, J.P., Thomas, E.K., Wilson, C.R., Wolfe, A.P., 2009b. Recent changes in a remote Arctic lake are unique within the last 200,000 years. Proc. Natl. Acad. Sci. U.S.A. 106, 18443–18446.

Battarbee, R.W., Jones, V.I., Flower, R.J., Cameron, N.G., Bennion, H., Carvalho, L., Juggins, S., 2001. Diatoms. In: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), Tracking Environmental Change Using Lake Sediments, vol. 3. Kluwer Academic Publishers, The Netherlands, pp. 155–202.

Battarbee, R.W., Charles, D.F., Bigler, C., Cumming, B.F., Renberg, I., 2010. Diatoms as indicators of surface water acidity. In: Smol, J.P., Stoermer, E.F. (Eds.), The Diatoms: Applications for the Environmental and Earth Sciences, second ed. Cambridge University Press, pp. 98–121.

Berger, A., Loutre, M.F., 2002. An exceptionally long interglacial ahead? Science 297, 1287–1288.

Brigham-Grette, J., Melles, M., Minyuk, P., Party, Scientific, 2007. Overview and significance of a 250 ka paleoclimate record from El'gygytgyn Crater Lake, NE Russia. J. Paleolimnol. 37, 1–16.

Briner, J.P., Miller, G.H., Davis, P.T., Finkel, R.C., 2005. Cosmogenic exposure dating in arctic glacial landscapes: implications for the glacial history of northeastern Baffin Island, Arctic Canada. Can. J. Earth Sci. 42, 67–84.

Briner, J.P., Michelutti, N., Francis, D.R., Miller, G.H., Axford, Y., Wooler, M.J., Wolfe, A.P., 2006. A multi-proxy lacustrine record of Holocene climate change on northeastern Baffin Island, Arctic Canada. Quat. Res. 65, 431–442.

Briner, J.P., Overeem, I., Miller, G., Finkel, R., 2007a. The deglaciation of Clyde Inlet, northeastern Baffin Island, Arctic Canada. J. Quat. Sci. 22, 223–232.

Briner, J.P., Axford, Y., Forman, S.L., Miller, G.H., Wolfe, A.P., 2007b. Multiple generations of interglacial lake sediment preserved beneath the Laurentide Ice Sheet. Geology 35, 887–890.

CAPE Project Members, 2001. Holocene paleoclimate data from the Arctic: testing models of global climate change. Quat. Sci. Rev. 20, 1275–1287.

Charles, D.F., 1991. Acidic Deposition and Aquatic Ecosystems. Regional Case Studies. Springer-Verlag Inc, New York.

Cherapanova, M.V., Snyder, J.A., Brigham-Grette, J., 2007. Diatom stratigraphy of the last 250 ka at Lake El'gygytgyn, northeast Siberia. J. Paleolimnol. 37, 155–162.

Dean, W.E., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. J. Sed. Petrol 44, 242–248.

Deevey, E.S., 1942. Studies on Connecticut lake sediments. III. The biostratonomy of Linsley Pond. Am. J. Sci. 240, 233–264.

Desprat, S., Goñi, M.F.S., Turin, J.L., Duprat, J., Malaize, B., Peypouquet, J.P., 2006. Climatic variability of Marine Isotope Stage 7: direct land-sea-ice correlation from a multiproxy analysis of a north-western Iberian margin deep-sea core. Quat. Sci. Rev. 25, 1010–1026.

de Vernal, A., Miller, G.H., Hillaire-Marcel, C., 1991. Paleoenvironments of the Last Interglacial in northwest North Atlantic region and adjacent mainland Canada. Quat. Int. 10–12, 95–106.

Douglas, M.S.V., Smol, J.P., Blake Jr., W., 1994. Marked post-18th century environmental change in high-arctic ecosystems. Science 266, 416–419.

Douglas, M.S.V., Smol, J.P., 2010. Freshwater diatoms as indicators of environmental change in the High Arctic. In: Smol, J.P., Stoermer, E.F. (Eds.), The Diatoms: Applications for the Environmental and Earth Sciences, second ed. Cambridge University Press, Cambridge, pp. 249–266.

Engstrom, D.R., Fritz, S.C., Almendinger, J.E., Juggins, S., 2000. Chemical and biological trends during lake evolution in recently deglaciated terrain. Nature 408, 161–166.

Environment Canada, 2004. Canadian Climate Normals 1971–2000. http://climate.weatheroffice.ec.gc.ca/climate_normals/results_e.html?StnID=1743&;autofwd1.
Francis, D.R., Wolfe, A.P., Walker, I.R., Miller, G.H., 2006. Interglacial and Holocene temperature reconstructions based on midge remains in sediments of two lakes from Baffin Island, Nunavut, Arctic Canada. Palaeogeog. Palaeoclimatol. Palaeoecol. 236, 107–124.
Fréchette, B., Wolfe, A.P., Miller, G.H., Richard, P.J.H., de Vernal, A., 2006. Vegetation and climate of the last interglacial on Baffin Island, Arctic Canada. Palaeogeog. Palaeoclimatol. Palaeoecol. 236, 91–106.
Fréchette, B., de Vernal, A., Richard, P.J.H., 2008. Holocene and Last Interglacial cloudiness in eastern Baffin Island, Arctic Canada. Can. J. Earth Sci. 45, 1221–1234.
Graney, J.R., Halliday, A.N., Keeler, G.J., Nriagu, J.O., Robbins, J.A., Norton, S.A., 1995. Isotopic record of lead pollution in lake sediments from the northeastern United States. Geochim. Cosmochim. Acta 59, 1715–1728.
Grimm, E.C., 1993. Tilia (Version 2.0.b.4) and Tilia-Graph (Version 2.0.b.5). Illinois State Museum, Springfield, IL.
GRIP Members, 1993. Climate instability during the last interglacial period recorded in the GRIP ice core. Nature 364, 203–207.
Heiri, O., Lotter, A.F., Lemcke, G., 2001. Loss on ignition as a method for estimating organic carbonate content in sediments: reproducibility and comparability of results. J. Paleolimnol. 25, 101–110.
Hodgson, D.A., Verleyen, E., Squier, A.H., Sabbe, K., Keely, B.J., Saunders, K.M., Vyverman, W., 2006. Interglacial environments of coastal east Antarctica: comparison of MIS 1 (Holocene) and MIS 5e (Last Interglacial) lake-sediment records. Quat. Sci. Rev. 25, 179–197.
Johnsen, S.J., Dahl-Jensen, D., Gundestrup, N., Steffensen, J.P., Clausen, H.B., Miller, H., Masson-Delmotte, V., Sveinbjörnsdottir, A.E., White, J., 2001. Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and NorthGRIP. J. Quat. Sci. 16, 299–307.
Joynt, E.H., Wolfe, A.P., 2001. Paleoenvironmental inference models from sediment diatom assemblages in Baffin Island lakes (Nunavut, Canada) and reconstructions of summer water temperature. Can. J. Fish. Aquat. Sci. 58, 1222–1243.
Juggins, S., 2003. C2 Data Analysis. University of Newcastle, England.
Kaufman, D.S., Ager, T.A., Anderson, N.J., Anderson, P.M., Andrews, J.T., Bartlein, P.T., Brubaker, L.B., Coats, L.L., Cwynar, L.C., Duvall, M.L., Dyke, A.S., Edwards, M.E., Eisner, W.R., Gajewski, K., Geirsdottir, A., Hu, F.S., Jennings, A.E., Kaplan, M.R., Kerwin, M.W., Lozhkin, A.V., MacDonald, G.M., Miller, G.H., Mock, C.J., Oswald, W.W., Otto-Bliesner, B.L., Porinchu, D.F., Ruhland, K., Smol, J.P., Steig, E.J., Wolfe, B.B., 2004. Holocene thermal maximum in the western Arctic (0–180 degrees W). Quat. Sci. Rev. 23, 2059–2060.
Kerwin, M.W., Overpeck, J.T., Webb, R.S., Anderson, K.H., 2004. Pollen-based summer temperature reconstruction for the eastern Canadian boreal forest, subarctic, and Arctic. Quat. Sci. Rev. 23, 1901–1924.
Koinig, K.A., Schmidt, R., Sammaruga-Wögrath, S., Tessadri, R., Psenner, R., 1998. Climate change as the primary cause for pH shifts in a high arctic lake. Water Air Soil Pollut. 104, 167–180.
Krammer, K., Lange-Bertalot, H., 1986. Bacillariophyceae 1. Teil: Naviculaceae. In: Ettl, H., Gerloff, J., Heynig, H., Mollenhauer, D. (Eds.), Die Susswasserflora Mitteleuropa 2/1. Gustav Fischer Verlag, Stuttgart, Germany 876pp.
Krammer, K., Lange-Bertalot, H., 1988. Bacillariophyceae 2. Teil: Bacillariaceae, Epithemiaceae, Surirellaceae. In: Ettl, H., Gerloff, J., Heynig, H., Mollenhauer, D. (Eds.), Die Susswasserflora Mitteleuropa 2/2. Gustav Fischer Verlag, Stuttgart, Germany 596pp.
Krammer, K., Lange-Bertalot, H., 1991a. Bacillariophyceae 3. Teil: Centrales, Fragilariaceae, Eunotiaceae. In: Ettl, H., Gerloff, J., Heynig, H., Mollenhauer, D. (Eds.), Die Susswasserflora Mitteleuropa 2/3. Gustav Fischer Verlag, Stuttgart, Germany 576pp.
Krammer, K., Lange-Bertalot, H., 1991b. Bacillariophyceae 4. Teil: Achnanththaceae, Kritische Erganzungen zu Navicula (Lineolatae), und Gomphonema. In: Ettl, H., Gartner, G., Gerloff, J., Heynig, H., Mollenhauer, D. (Eds.), Die Susswasserflora Mitteleuropa 2/4. Gustav Fischer Verlag, Stuttgart, Germany 437pp.
Levac, E., de Vernal, A., Blake, W., 2001. Sea-surface conditions in northernmost Baffin Bay during the Holocene: palynological evidence. J. Quat. Sci. 16, 353–363.
Lewis, A.R., Marchant, D.R., Ashworth, A.C., Hedena, L., Hemming, S.R., Johnson, J.V., Leng, M.J., Machlus, M.L., Newton, A.E., Raine, I., Willenbring, J.K., Williams, M., Wolfe, A.P., 2008. Mid-Miocene cooling and the extinction of tundra in continental Antarctica. Proc. Natl. Acad. Sci. U.S.A. 105, 10676–10680.
Lotter, A.F., Bigler, C., 2000. Do diatoms in the Swiss Alps reflect the length of ice-cover? Aqua. Sci. 62, 125–141.
Michelutti, N., Wolfe, A.P., Vinebrooke, R.D., Rivard, B., Briner, J.P., 2005. Recent primary production increases in arctic lakes. Geophys. Res. Lett. 32, L19715.
Michelutti, N., Douglas, M.S.V., Wolfe, A.P., Smol, J.P., 2006. Heightened sensitivity of a poorly buffered high arctic lake to lake-Holocene climatic change. Quat. Res. 65, 421–430.
Michelutti, N., Wolfe, A.P., Briner, J.P., Miller, G.H., 2007. Climatically controlled chemical and biological development in Arctic lakes. J. Geophys. Res. 112, G03002.
Michelutti, N., Simonetti, A., Briner, J.P., Funder, S., Creaser, R.A., Wolfe, A.P., 2009. Temporal trends of pollution Pb and other metals in east-central Baffin Island inferred from lake sediment geochemistry. Sci. Tot. Environ. 407, 5653–5662.
Miller, G.H., Andrews, J.T., Short, S.K., 1977. The last interglacial-glacial cycle, Clyde Foreland, Baffin Island, N.W.T.: stratigraphy, biostratigraphy, and chronology. Can. J. Earth Sci. 14, 2824–2857.
Miller, G.H., Mode, W.N., Wolfe, A.P., Sauer, P.E., Bennike, O., Forman, S.L., Short, S.K., Stafford, T.W., 1999. Stratified interglacial lacustrine sediments from Baffin Island, Arctic Canada: chronology and paleoenvironmental implications. Quat. Sci. Rev. 18, 789–810.
Miller, G.H., Wolfe, A.P., Briner, J.P., Sauer, P.E., Nesje, A., 2005. Holocene glaciation and climate evolution of Baffin Island, Arctic Canada. Quat. Sci. Rev. 24, 1703–1721.
Moore, J.J., Hughen, K.A., Miller, G.H., Overpeck, J.T., 2001. Little Ice Age recorded in summer temperature reconstruction from varved sediments of Donard Lake, Baffin Island, Canada. J. Paleolimnol. 25, 503–517.
NGRIP members, 2004. High-resolution record of Northern Hemisphere climate extending into the last interglacial period. Nature 431, 147–151.
Patrick, R., Reimer, C.W., 1966. The Diatoms of the United States, vol. 1, Philadelphia, PA.
Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delayque, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pépin, L., Ritz, C., Saltzman, E., Stievenard, M., 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 399, 429–436.
Pienitz, R., Douglas, M.S.V., Smol, J.P., 2004. Paleolimnological research in polar regions. In: Pienitz, R., Douglas, M.S.V., Smol, J.P. (Eds.), Long-term Environmental Change in Arctic and Antarctic Lakes. Springer, New York, pp. 1–17.
Podritske, B., Gajewski, K., 2007. Diatom community response to multiple scales of Holocene climate variability in a small lake on Victoria Island, NWT, Canada. Quat. Sci. Rev. 26, 3179–3196.
Renberg, I., 1990. A 12,600 year perspective on the acidification of Lilla Öresjön, southwest Sweden. Philos. Trans. R. Soc. B 327, 357–361.
Rühland, K., Smol, J.P., 2005. Diatom shifts as evidence for recent Subarctic warming in a remote tundra lake, NWT, Canada. Palaeogeog. Palaeoclimatol. Palaeoecol. 226, 1–16.
Serreze, M.C., Walsh, J.E., Chapin III, F.S., Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W.C., Morison, J., Zhang, T., Barry, R.G., 2000. Observational evidence of recent change in the northern high-latitude environment. Clim. Change 46, 159–207.
Serreze, M.C., Francis, J.A., 2006. The Arctic amplification debate. Clim. Change 76, 241–264.
Short, S.K., Mode, W.N., Davis, P.T., 1985. The Holocene record from Baffin Island: modern and fossil pollen studies. In: Andrews, J.T. (Ed.), Quaternary Environments, Eastern Canadian Arctic, Baffin Bay and Western Greenland. Allen and Unwin Inc., Winchester, Mass, pp. 608–642.
Siegenthaler, U., Stocker, T.F., Monnin, E., Lüthi, D., Schwander, J., Stauffer, B., Raynaud, D., Barnola, J.-M., Fischer, H., Masson-Delmotte, V., Jouzel, J., 2005. Stable carbon cycle – climate relationship during the Late Pleistocene. Science 310, 1313–1317. doi:10.1126/science.1120130.
Smol, J.P., 1983. Paleophycology of a high arctic lake near Cape Herschel, Ellesmere Island. Can. J. Bot. 61, 2195–2204.
Smol, J.P., 1988. Paleoclimate proxy data from freshwater Arctic diatoms. Verh. Int. Verein. Limnol. 23, 837–844.
Smol, J.P., Wolfe, A.P., Birks, H.J.B., Douglas, M.S.V., Jones, V.J., Korhola, A., Pienitz, R., Rühland, K., Sorvari, S., Antoniades, D., Brooks, S.J., Fallu, M.-A., Hughes, M., Keatley, B.E., Laing, T.E., Michelutti, N., Nazarova, L., Nyman, M., Paterson, A.M., Perren, B., Quinlan, R., Rautio, L., Saulnier-Talbot, E., Siitonen, S., Solovieva, N., Weckström, J., 2005. Climate driven regime shifts in the biological communities of arctic lakes. Proc. Natl. Acad. Sci. U.S.A. 102, 4397–4402.
Smol, J.P., Douglas, M.S.V., 2007. From controversy to consensus: making the case for recent climate change in the Arctic using lake sediments. Front. Ecol. Environ. 5, 466–474.
Steig, E.J., Wolfe, A.P., Miller, G.H., 1998. Wisconsinan refugia and the glacial history of eastern Baffin Island, Arctic Canada: coupled evidence from cosmogenic isotopes and lake sediments. Geology 26, 835–838.
Stroeven, A.P., Fabel, D., Hättestrand, C., Harbor, J., 2002. A relict landscape in the center of Fennoscandian glaciation: cosmogenic radionuclide evidence of tors preserved through multiple glacial cycles. Geomorphology 44, 145–154.
Teller, J.T., Leverington, D.W., 2004. Glacial Lake Agassiz: a 500 yr history of change and its relationship to the $\delta^{18}O$ record of Greenland. GSA Bull. 116, 729–742.
ter Braak, C.J.F., Šmilauer, P., 2002. CANOCO Reference Manual and CanoDraw for Windows User's Guide: Software for Canonical Community Ordination (version 4.5). Microcomputer Power, Ithaca, NY. 500pp.
Thomas, E.K., Axford, Y., Briner, J.P., 2008. Rapid 20th century environmental change on northeastern Baffin Island, Arctic Canada inferred from a multi-proxy lacustrine record. J. Paleolimnol. 40, 507–517.
Tzedakis, P.C., 1994. Hierarchical biostratigraphical classification of long pollen sequences. J. Quat. Sci. 9, 257–259.
Van Dam, H., Mertens, A., Sinkeldam, J., 1994. A coded checklist and ecological indicator values of freshwater diatoms from the Netherlands. Nether. J. Aquat. Ecol. 28, 117–133.
Viau, A.E., Gajewski, K., Sawada, M.C., Fines, P., 2006. Millennial-scale temperature variations in North America during the Holocene. J. Geophys. Res. 111, D09102.
Wilson, C.R., 2009. A lacustrine sediment record of the last three interglacial periods from Clyde Foreland, Baffin Island, Nunavut: biological indicators from the past 200,000 years. M.Sc. Thesis, Queen's University, Kingston, Ontario.

Williams, L.D., Bradley, R.S., 1985. Paleoclimatology of the Baffin Bay region. In: Andrews, J.T. (Ed.), Quaternary Environments, Eastern Canadian Arctic, Baffin Bay and Western Greenland. Allen and Unwin Inc., Winchester, Mass, pp. 741–772.
Woillard, G., 1978. Grande Pile peat bog: a continuous pollen record for the last 140 000 years. Quat. Res. 9, 1–21.
Wolfe, A.P., 1996a. A high-resolution late-glacial and early Holocene diatom record from Baffin Island, eastern Canadian Arctic. Can. J. Earth Sci. 33, 928–937.
Wolfe, A.P., 1996b. Spatial patterns of modern diatom distribution and multiple paleolimnological records from a small arctic lake on Baffin Island, Arctic Canada. Can. J. Bot. 74, 435–449.
Wolfe, A.P., Härtling, J.W., 1996. The late Quaternary development of three ancient tarns on southwestern Cumberland Peninsula, Baffin Island, Arctic Canada: paleolimnological evidence from diatoms and sediment chemistry. J. Paleolimnol. 15, 1–18.
Wolfe, A.P., Fréchette, B., Richard, P.J.H., Miller, G.H., Forman, S.L., 2000. Paleoecology of a >90,000-year lacustrine sequence from Fog Lake, Baffin Island, Arctic Canada. Quat. Sci. Rev. 19, 1677–1699.
Wolfe, A.P., 2002. Climate modulates the acidity of Arctic lakes on millennial time scales. Geology 30, 215–218.
Wolfe, A.P., 2003. Diatom community responses to late-Holocene climatic variability, Baffin Island, Canada: a comparison of numerical approaches. Holocene 13, 29–37.
Wolfe, A.P., Smith, I.R., 2004. Paleolimnology of the middle and high Canadian Arctic. In: Pienitz, R., Douglas, M.S.V., Smol, J.P. (Eds.), Long-term Environmental Change in Arctic and Antarctic Lakes. Springer, Netherlands, pp. 241–268.
Wolfe, A.P., Miller, G.H., Olsen, C., Forman, S.L., Doran, P.T., Holmgren, S.U., 2004. Geochronology of high latitude lake sediments. In: Pienitz, R., Douglas, M.S.V., Smol, J.P. (Eds.), Long-Term Environmental Change in Arctic and Antarctic Lakes. Springer, New York, pp. 19–52.