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Holocene climate inferred from biological (Diptera: Chironomidae) analyses in a Southampton Island (Nunavut, Canada) lake

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Abstract: Concerns about the effects of global warming on Arctic environments have stimulated multidisciplinary research into the history of their long-term climatic and environmental variability to improve future predictions of climate in these remote areas. Here we present the first palaeolimnological study for Southampton Island using analyses of chironomids supported by sedimentological analyses, carried out on a 1 m long core retrieved from a lake located in the northeastern part of the island. This core was made up of marine sediments underneath 65 cm of freshwater lake sediments. A marine shell, humic-acids and chironomid head capsules were used to date this sequence. The Holocene environmental history of the lake consisted of two major contrasting periods. The first one, between about 5570 and 4360 cal. yr BP, was climatically unstable, with common postglacial chironomid taxa such as *Corynocera oliveri*-type, *Paracladius* and *Microspectra radialis*-type. This period also corresponded to the highest chironomid-inferred August air temperature (10°C) for the whole record and to significant increases in major chemical elements as detected by x-ray fluorescence. During the second period, which lasted from about 3570 cal. yr BP until the present, limnological conditions seemed to stabilize after a change to cold oligotrophic chironomid taxa, such as *Heterotrissocladius subpilosus*-group, with no major variations in the abundance of chemical elements. Inferred August air temperatures ranged between 8 and 9°C. This study provided unique information on the timing of the Holocene Thermal Maximum in the Foxe Basin area, a region with very little information available on long-term climate change. This region showed, so far, relatively few signs of recent climatic change, as opposed to other regions in the High Arctic.

Key words: Southampton Island, Canadian Arctic, Holocene climate reconstruction, chironomids, x-ray fluorescence, lacustrine–marine transition.

Introduction

Instrumental records obtained from regions surrounding the Foxe Basin, Hudson Bay and Hudson Strait revealed that these regions were little affected by global warming, showing only slight increases (< 0.5°C) in mean annual air temperature over the last 50 years and even a cooling during the winter season (Serreze *et al.*, 2000; Arctic Climate Impact Assessment (ACIA), 2005). These results are in sharp contrast to the warming observed in other arctic regions (Smol *et al.*, 2005), including northwestern Canada, Alaska and the Canadian High Arctic. This discrepancy and the recent concerns about the effects of global warming on arctic ecosystems increase the need to extend our knowledge of the spatial and temporal aspects of natural climatic variations. However, neither instrumental records nor climatic models developed for arctic regions provide past and future climatic scenarios of

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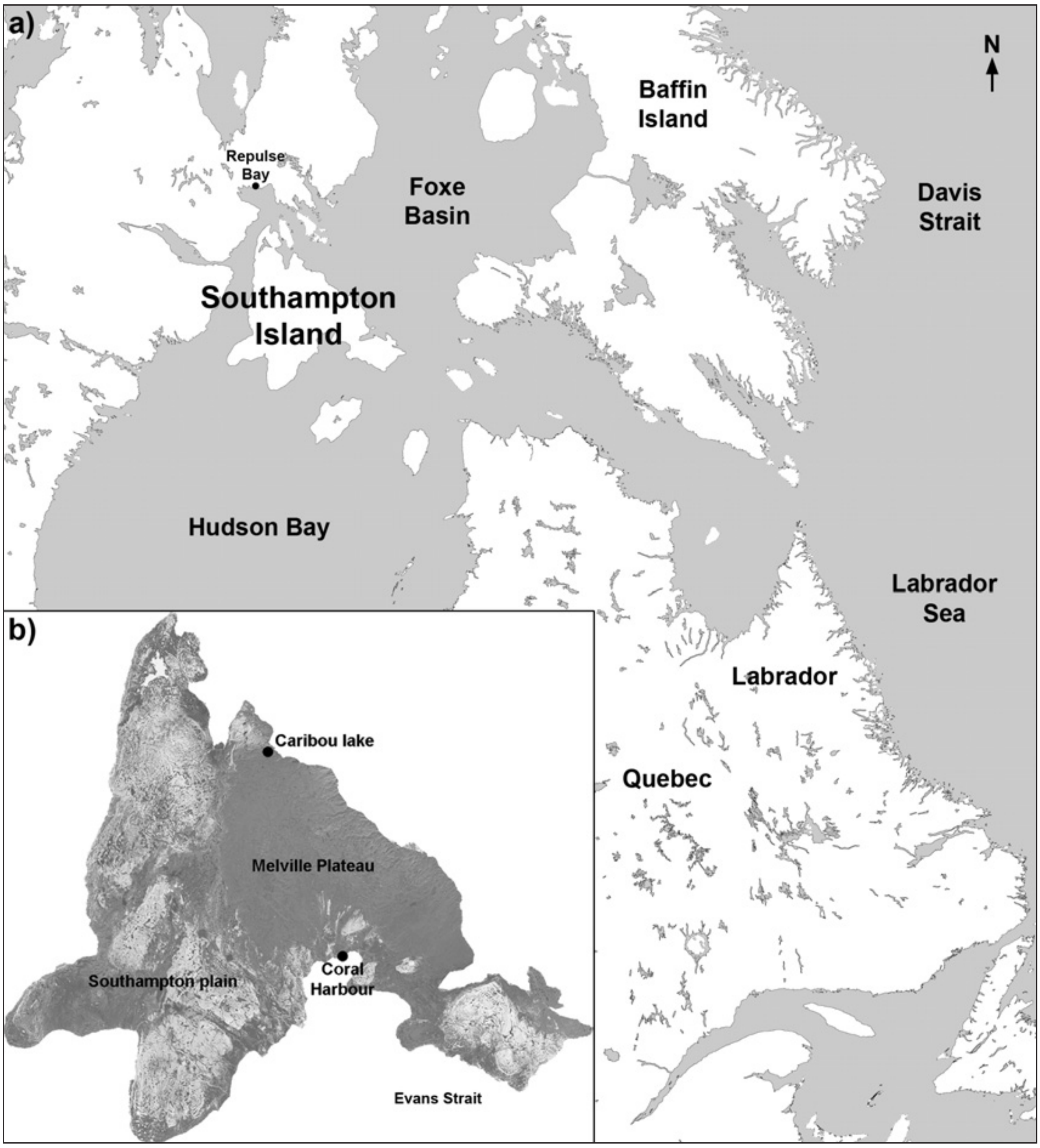

Figure 1 Location of Southampton Island (a), and Caribou Lake (b)

sufficient spatial and temporal resolution. The available instrumental records cover only short time spans, now referred to as the 'Anthropocene' period (Crutzen, 2002), that were already affected by anthropogenic activities and therefore might not be representative of natural climate variation in the study region. Climate model outputs should thus be validated through comparison with pre-existing conditions (eg, Battarbee, 2000).

Combined with recent developments in statistical inference models, lake-sediment archives and their proxies have (indirectly) extended environmental 'monitoring' beyond the Anthropocene to hundreds and thousands of years before present (BP). The use of biological and sedimentological indicators has provided new tools to quantitatively reconstruct physical and chemical variables through the history of the studied lakes (Smol *et al.*, 2001; Pienitz *et al.*, 2004a). Chironomids (Insecta: Diptera: Chironomidae) are the most abundant insects preserved in lake sediments and can be used to infer physical and chemical variables such as air (eg, Larocque *et al.*, 2006) and water temperature (eg, Walker *et al.*, 1991), total phosphorus (eg, Langdon *et al.*, 2006), oxygen availability (Quinlan *et al.*, 1998), lake-water depth (Korhola *et al.*, 2000) and chlorophyll-a (Brodersen and Lindegaard, 1999). With their short response time to environmental shifts, these zoological indicators can provide critical information on the effects of past climatic variations on the lake's aquatic communities.

The use of sedimentological indicators, such as grain size and geochemical components, provides an extended overview of the palaeohydrological, chemical and physical conditions in the studied lake and its surrounding watershed (Last, 2001). Texture of lake sediments is a valuable tool to reconstruct past hydrological conditions that have affected the sedimentary lake processes (eg, Folk, 1966) and, by extension, which may have controlled the biological communities. Inorganic geochemical analysis of the sediments provides important information on mineral inputs within the lake ecosystem (St-Onge *et al.*, 2007).

Located at the boundary between the Hudson Bay and the Foxe Basin (Figure 1a), Southampton Island might represent a frontier or transitional zone in a rapidly changing Canadian Arctic. Studies on sites located north of Southampton Island (Ellesmere and Baffin Islands) indicated a rapid and recent change in diatom and chironomid communities, probably associated with warming, whereas communities from sites located south of Southampton Island (eg, northern Québec and Labrador) still showed little sign of change (Pienitz *et al.*, 2004b; Smol *et al.*, 2005; Saulnier-Talbot, 2007). Despite its central position in this region, studies conducted on this island have mainly focused on its Quaternary geology (Bird, 1953; Heywood and Sanford, 1976), and geomorphology (Rouault, 2006).

Here we present the first palaeolimnological study of Southampton Island, using chironomid and sedimentological indicators in an attempt to refine the knowledge of past climatic variability in this region. In addition, this study provides new dates for eustatic rebound and complements information already available for the Melville Peninsula (Dredge, 2001).

Study sites

With an area of 40 663 km², Southampton Island consists of two physiographic subdivisions: (1) a mountainous area made of Precambrian rocks called Melville Plateau extending over the whole eastern part of the island, and (2) the Southampton plain, covering the western part of the island and underlained by Palaeozoic rocks (Heywood and Sanford, 1976) (Figure 1b). Marine deposits commonly encountered below ~ 150 m a.s.l., implied to Dredge (2001) that deglaciation occurred around 7500–7000 cal. yr BP in southern Southampton Island and 6900 cal. yr BP in its northern part. However, a study in 2005 refined this information and revealed that deglaciation occurred from 8300 to 8200 cal. yr BP for the southeastern part of the Island, and 6700 to 6600 cal. yr BP for the Melville Plateau (Rouault, 2006). Mean annual temperatures recorded at Coral Harbour airport (64°12′0″N, 83°22′0″W) was −11.5°C (1945–2002) and −10.6°C (1993–2002) (Environment Canada, 2002).

Located 155 m a.s.l. near Cape Bylot in the northeastern mountainous area of the island, our sampling site (Caribou Lake, unofficial name (65°12′45″N, 83°47′49″W); Figure 1b) is of elongate shape (~ 500 m × ~ 170 m) with a maximum lake depth of 19 m. The lake is bordered by a steep cliff on its northern side and a gentle slope on its southern side. At the time of sediment sampling in July 2004, the lake shore was littered with large blocks and boulders and the surrounding arctic tundra vegetation was mainly composed of Ericaceae (*Cassiope tetragona* (L.) D. Don), Rosaceae (*Dryas integrifolia* Vahl), and Salicaceae (*Salix arctica* Pallas).

Materials and methods

Sampling and pre-analysis of the core

A 1 m long core (4P) was retrieved from the deepest part of Caribou Lake with a percussion corer (diameter = 7 cm) from Aquatic Research. The core was transported intact inside its sampling tube to our laboratory facilities and stored at 4°C.

A computed axial tomography imaging (CAT Scan) of the sediment core was achieved with a Siemens Somatom scanner at the Institut National de la Recherche Scientifique, Eau-Terre-Environnement (INRS-ETE), in Québec City (Duchesne *et al.*, 2006; St-Onge *et al.*, 2007). The entire core was scanned through a rotating array of x-rays (with lower and higher x-ray attenuation represented in a 2D negative image by darker and lighter zones, respectively) at a resolution of 0.1 cm × 0.1 cm to detect laminations, as well as to determine the appropriate plane for sectioning of the core with a rotary tool and a fine iron wire.

Non-destructive analyses

A geochemical analysis of the core was made with an ITRAX™ core scanner from the GIRAS laboratory (INRS-ETE). A general description of this tool is provided in Croudace *et al.* (2006). In addition to providing major chemical-element profiles along the core with x-ray fluorescence (XRF), this scanner produced high-definition optical images and radiography profiles (x-ray) of the core (St-Onge *et al.*, 2007). The x-ray profile is represented as a 2D positive image of the core, with lower x-ray attenuation represented by lighter zones and higher ones represented by darker zones. A voltage of 40 kV, a current of 40 mA, an exposure time of 425 ms and a step size at 100 μm were used for the radiography profile. The XRF analysis was done with a molybdenum x-ray tube at a step-size of 1000 μm with a voltage of 30 kV, a current of 25 mA and a 10 s exposure time.

Destructive analyses

The half-sectioned core used for the ITRAX™ analysis was subsampled every 0.5 cm and all the subsamples were freeze-dried for 24 h. Grain-size analysis was made every 2 cm on ~ 0.3 g of freeze-dried sediment. Samples were first treated in a hydrogen peroxide solution (30% v/v) to remove organic residue and in a 1 M sodium hydroxide solution to remove biogenic silica. The particle-size distribution was then determined with a Fritsch Analysette 22 laser particle sizer, and the results were plotted as a two-dimensional contour plot (Beierle *et al.*, 2002) with SigmaPlot. Boundaries for the particle-size distribution follow Last (2001). An estimation of the sediment organic-matter content was calculated by loss-on-ignition (LOI) at 550°C following Heiri *et al.* (2001). The analysis of total carbon, nitrogen and sulphur content (CNS) was also made on a LECO CHNS-932.

Chironomid head capsules were retrieved every 1 cm in the uppermost 10 cm and at 2 cm intervals through the rest of the core. At least 1 g of freeze-dried sediment was treated for 10 min in a hot (not boiling) 10% KOH solution. The solution was then sieved on a 100 μm mesh, and the residue retained on the mesh was used for extracting midge remains. Head capsules were collected from the sediments with the kerosene-flotation technique (Rolland and Larocque, 2006). The remaining solution was placed in a Bogorov counting tray and examined under a stereomicroscope at 35–60 × magnification. All head capsules picked were mounted ventral side facing up on a microscope slide with a water-soluble mounting medium (Hydro-Matrix). At least 50 head capsules (Larocque, 2001; Heiri and Lotter, 2001; Quinlan and Smol, 2001) were identified under a light microscope at 400 × magnification with the help of various taxonomic guides such as Cranston (1982), Oliver and Roussel (1983), Wiederholm (1983) and a new visual guide based on high-resolution pictures (Larocque and Rolland, 2006). Tanytarsini taxa were separated with Brooks *et al.* (1997) and Brooks unpublished identification keys which are now part of a new taxonomic guide by Brooks *et al.* (2007). In the absence of mandibles, the Tanytarsini were classified by the presence (Tanytarsini with) or absence (Tanytarsini without) of a spur on their antennal pedicel. When no antennal pedicel was present they were placed in the Tanytarsini sp. category. The Tanypodinae were separated by the position of the setae, following Rieradevall and Brooks (2001). Identification of *Zalutschia* sp. B followed Barley *et al.* (2006). Fragments with more than half a head capsule were counted as one head capsule, whereas capsules that were exactly half one head capsule were counted as half. All other fragments were disregarded.

Dating of the sediment sequence (Table 1) was based on two calibrated AMS radiocarbon dates from chironomid head capsules (44.5–45.5 cm and 62 cm) and one marine shell (*Macoma balthica*) found at the bottom of the core (80.5 cm). Owing to the absence of any terrestrial macrofossil remains in the sediments, we also used three calibrated humic-acid dates from another core (core 3G), not described in this paper, but also retrieved at the same location in July 2004 and subsampled at 0.25 cm intervals in the field (Laperrière, 2006). The carbon dates obtained were converted to radiocarbon years Before Present (BP) using the program

Table 1 AMS radiocarbon dates from Caribou Lake (humic-acids, marine shell and chironomids)

Laboratory number	Core ID	Depth (cm)	Depth (cm) transposed to core 4P[a]	Material	^{14}C age BP	δ^{13}C	Cal. age BP	
							1σ (68.3%)	2 σ (95.4%)
UCI-21586	3G	10.25–10.75	6.5	Humics	1660 ± 25l	–25.2	1598–1529	1688–1517
UCI-21589	3G	24.75–25.25	15.8	Humics	2585 ± 25	–25.7	2748–2726	2757–2620
UCI-21585	3G	35.75–36.25	22.8	Humics	3285 ± 25	–24.6	3557–3472	3569–3450
Beta-222049	4P	44.5–45.5	–	Chironomids	6120 ± 40	–27.6	7010–6920	7160–6880
Beta-220586	4P	62–62.5	–	Chironomids	8370 ± 40	–26.7	9460–9320	9490–9290
UCI-28832	4P	80–81	–	Marine shell	7925 ± 20	3.6	6334–6204	6381–6109

The calibrated age ranges are based on the INTCAL98 and Marine04 calibration using CALIB 5.0.1 (Stuiver *et al*., 2005). Laboratories used were the Keck Carbon Cycle AMS Facility, Earth System Science Department, UC Irvine (UCI) and Beta Analytic in Miami, Florida.

[a] See text for details of core parallelization.

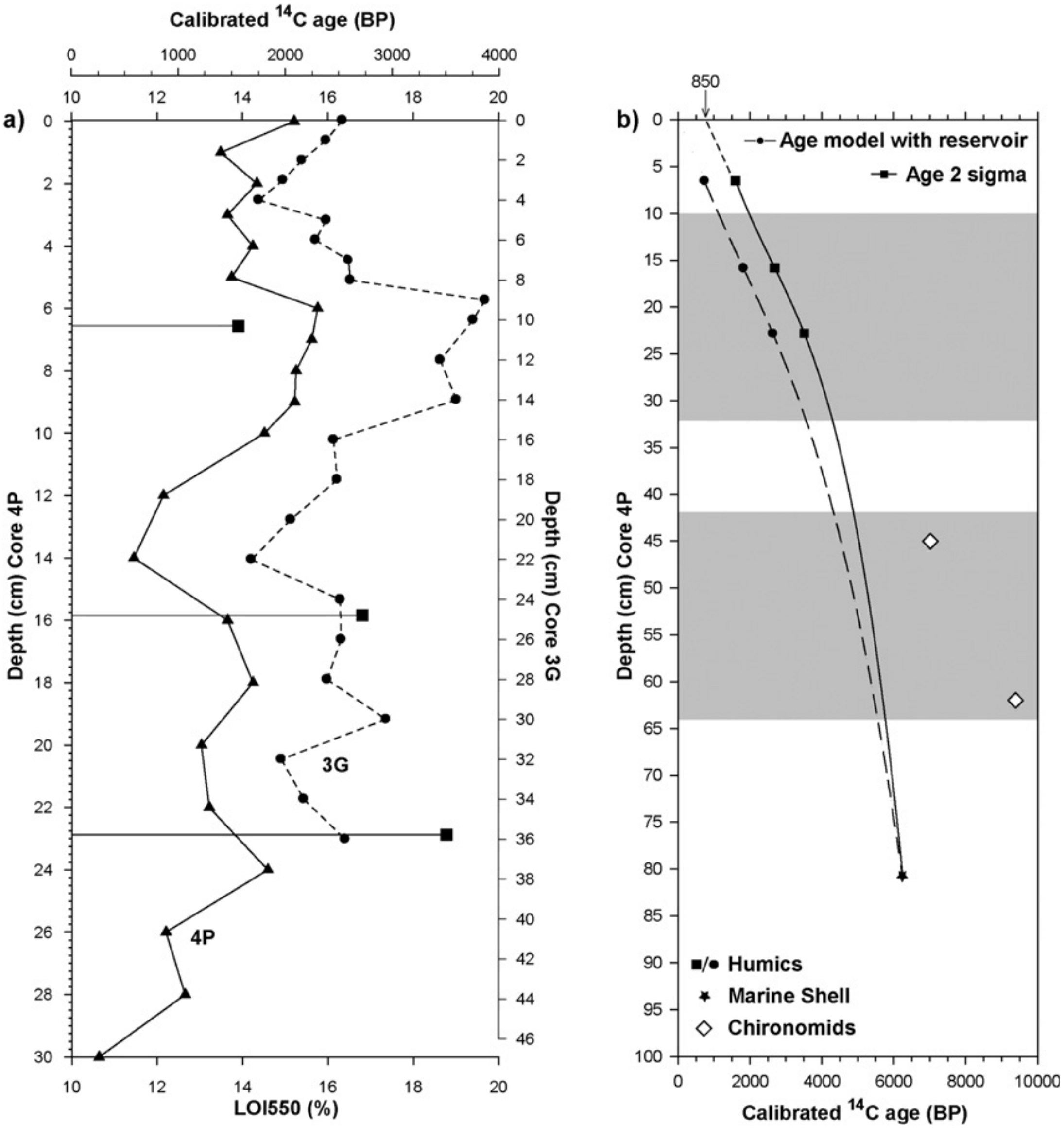

Figure 2 (a) Loss-on-ignition (LOI) at 550°C for core 4P (solid line with triangles) and core 3G (dashed line with circles). Depth axis of core 4P was stretched to match LOI variation in core 3G (see text). Calibrated humic-acid ^{14}C ages in core 3G are also provided (square symbols). These dates were transposed to core 4P depth axis. (b) Depth–age models for core 4P using marine shell (81 cm) and humic-acid dates derived from correlation with core 3G by LOI values. See text for more details on both models. Shaded areas indicate zones derived from the chironomid analysis

CALIB version 5.0.1 (Stuiver *et al.*, 2005). The marine calibration for the shell includes a local reservoir effect of (Delta) δR 200 ± 50 years derived from the Evans Strait and Repulse Bay (Nunavut) regions that surround Southampton Island. For the chironomid dating, at least 1200 clean head capsules were hand-picked from the sediment as described by Fallu *et al.* (2004) and processed by Beta Analytic in Miami, Florida, USA, following an acid/alkali/acid pretreatment. The humic-acids and the marine shell were dated at the Keck Carbon Cycle AMS Facility, Earth System Science Department, UC Irvine, USA. Taking into account the compaction effect in the core 4P during transport and storage, core correlation was made by depth from the water–sediment interface and by matching of the LOI information available in each core (Figure 2a).

Statistical analyses

Selected chemical elements (peak areas) and the abundance per gram and relative abundance of major chironomid taxa were represented in stratigraphic diagrams with the program C2 (Juggins, 2003). For the chironomid data a Hill's N1 diversity index (Hill, 1973) was calculated with Primer 6 (Clarke and Gorley, 2006). Zonation methods followed the recommendations of Birks and Gordon (1985) and Bennett (1996). Numerical zonation was carried out by optimal partitioning using sum of squares criteria (programs TRAN (Version 1.8; Juggins 1992a) and ZONE (Version 1.2; Juggins 1992b)) and the number of statistically significant zone limits was determined with the broken-stick model (software BSTICK version 1.0; Bennett, 1996). A Detrended Correspondence Analysis (DCA), with square root transformation and downweighting of rare taxa, was run to estimate the amount of chironomid-assemblage turnover along the length of the core (Bigler *et al.*, 2006). The gradient length of the first axis (>2) indicated a unimodal distribution (Lepš and Šmilauer, 2003) of the chironomid assemblages.

Chironomid assemblages (calculated as relative abundance) served to reconstruct mean August air temperatures with weighted averaging partial least squares (WA-PLS) analysis with a leave-one-out cross-validation method and a square root transformation. The calibration data set used for this reconstruction is derived from a model developed for northern Québec (Larocque *et al.*, 2006) with a coefficient of determination (r^2) of 0.76, a root mean square error of prediction (RMSEP) of 1.12°C, and a maximum bias of 2.14°C. The 'validity' of the transfer function was estimated by various statistical methods: (1) the fit-to-temperature, (2) the presence of modern analogues and (3) the percentage of taxa present in the fossil records and in the transfer function. These statistical analyses follow recommendations by Birks (1998). Samples from the core were passively plotted in the CCA (not shown here) of the transfer function to determine if the fossil samples were similar to the training set samples, and thus determine if the transfer function can be applied. All fossil samples were well within the training set samples indicating that (1) all fossils samples were similar to those found in the training set lakes and (2) that the transfer function can be applied.

Results

Core chronology

Correlation of core chronologies as shown in Figure 2 revealed that compaction occurred in the core that was not subsampled in the field and transported intact to the laboratory. Thus, matching of the two LOI curves required 'linear stretching' of this studied core by 13 cm, which corresponds to the difference in length measured in the field. Following this 13 cm linear stretch, both LOI curves presented the same trends and therefore allowed us to take the humic-acid dates into consideration for our core chronology (Figure 2a). The humic-acid dates obtained on core 3G were then transposed to core 4P. Chironomid-based dates (7020 cal. yr BP and 9390 cal. yr BP) were particularly older than the estimated time of deglaciation in the area (6600–6700 cal. yr BP) (Dredge, 2001; Rouault, 2006) and have therefore been disregarded to establish our age model (Figure 2b). Using both humic-acid dates and the marine shell date (calibrated age 2 sigma), a cubic regression model (Equation (1)) was then calculated (Figure 2b). The intercept of this curve with the age axis revealed a 'reservoir age' of the lake and its surrounding watershed of 850 years. This 'reservoir age', which may have biased the humic-acid dates, was then subtracted from these dates, and a second age model (Equation (2)) was then established and used as a reference for our core chronology.

$$y = -18.8794 + 0.0235x - 5.9896.10^{-6}\,x^2 + 7.6534.10^{-10}x^3 \quad (1)$$

$$\mathrm{y} = -1.1207 + 0.0112x - 1.6656.10^{-6}\,x^2 + 3.1459.10^{-10}x^3 \quad (2)$$

Geochemical and sedimentary analyses

The optical image, the two-dimensional scan (topogram), the XRF profiles of major chemical elements (plotted as peak area), and the x-ray image from ITRAX with its grey profile are provided in Figure 3. This series of analyses revealed that the core consisted of two principal units: marine and lake sediments. The marine sediments (100–64 cm core depth) were characterized by low penetration of x-rays and a high content of Ca and K. They also included many shells and pebbles. The transition from marine to lacustrine sediments at 64 cm was characterized by an abrupt change in the sediment composition, with a sharp decline in Ca concentrations and a higher porosity to x-rays as revealed by higher grey values.

Except for Sr and Zr, which declined through time, the profiles of all the selected chemical elements (Fe, Ti, Ca, K, Mn) in the lake sediments fluctuated without any visible trend from 64 to 42 cm. Only two high-magnitude declines in the peak area at 60 and 48 cm interrupted this relative stability and were correlated with holes in the half core surface (see optical image). Between 42 and 32 cm, these elements increased by ~ 30%, with a maximum of 50% for Fe and Ti. From 32 cm upwards, these profiles stabilized up to the top of the core and were only interrupted by two short-lived events, namely a minimum at 25 cm and a peak at 14 cm. Redox processes perturbed the Fe and Mn profiles in the uppermost 4 cm of the core, as revealed by large increases of their peak area. The incoherent/coherent ratio, which may be used as an estimate of the sediment organic content (Cox, personal communication, 2006), did not vary significantly during the lake history.

The particle-size distribution (Figure 4) generally revealed well-sorted, strongly fine-skewed and platykurtic (plateau-like distribution) sediments. The mean grain size (μm) gradually decreased through the lake's history. The marine/lacustrine transition (64–60 cm) was characterized by highly variable grain size, especially at 64 cm, where very coarse silt (~ 30 μm) and medium boulder gravel (~ 600 μm) modes were present. From 60 cm depth to the top of the core, respective modes of each level generally belonged to very coarse silt except at 22 and 16 cm where a shift to coarse silt (~ 18 μm) occurred.

The CNS and LOI analyses (Figure 4) provided useful information on the total matter derived from aquatic and terrestrial environments. The total carbon/nitrogen ratio (C_{Tot}/N) fluctuated around a mean value of 7.8, typical for lakes with low inputs of organic matter from vascular plants in arctic tundra settings (Meyers and Lallier-Vergès, 1999). Following the marine/lacustrine transition and until 42 cm, this ratio and the relative contents of total carbon and nitrogen increased as a consequence of higher contributions from vascular plants (carbon) and phytoplankton

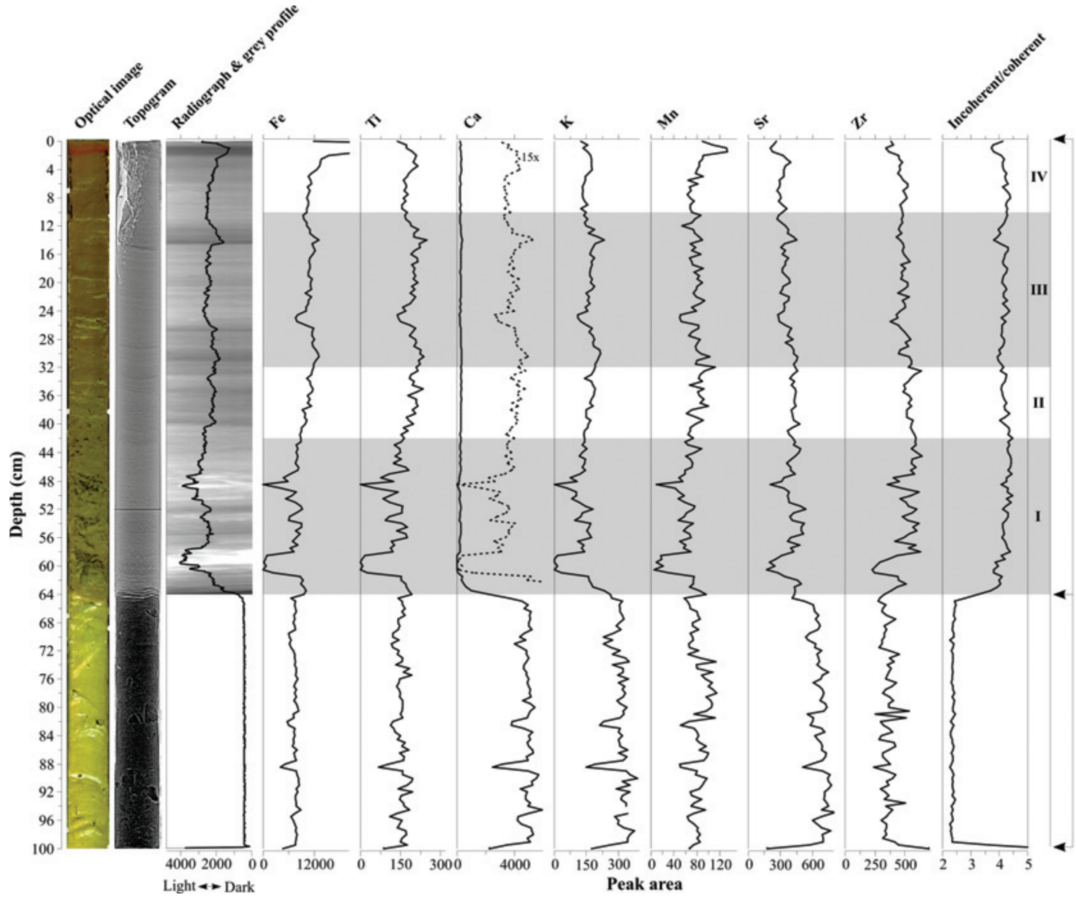

Figure 3 XRF profiles of major chemical elements (in peak area) of core 4P with an optical image of the half sectioned core, a two dimensional scan (topogram) of the core, and the x-ray image with its grey profile (reverse scale). X-ray image of the marine sediment is not provided as it was completely dark. Zones are derived from the chironomid analysis

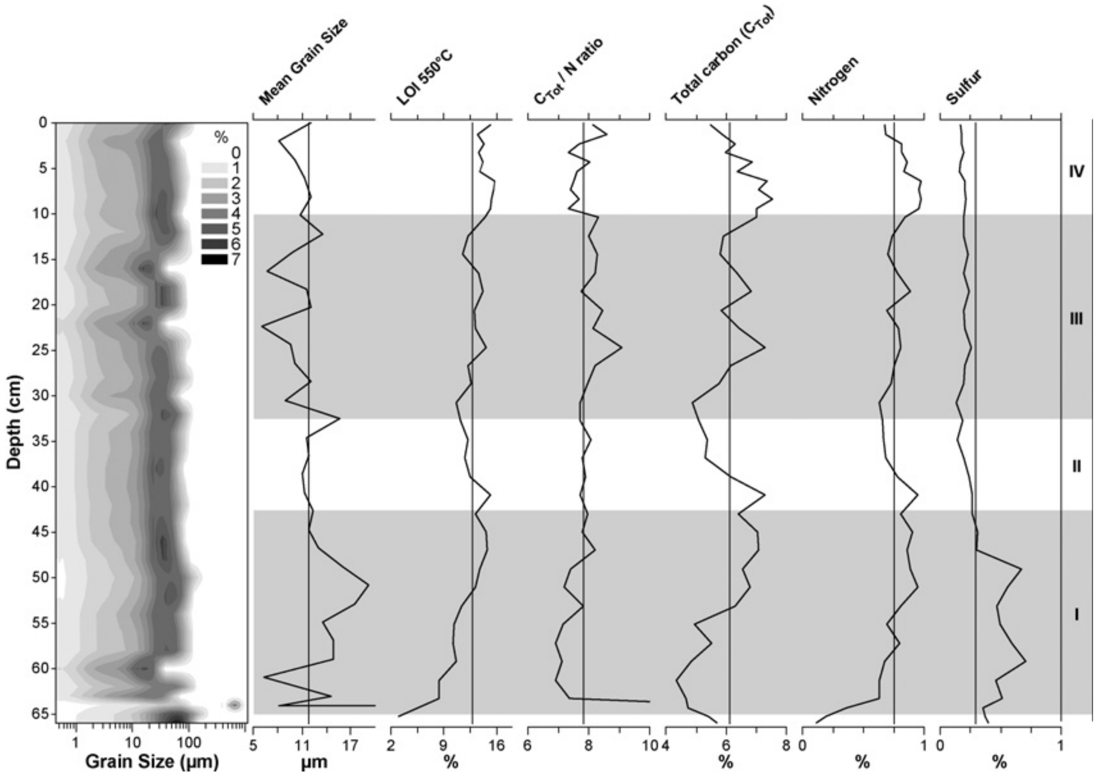

Figure 4 Two-dimensional graphic of the grain-size frequency distribution, with frequency values represented along a proportional grey scale from light to dark. Profiles of mean grain size, LOI at 550°C, C_T/N ratio, and total carbon, nitrogen and sulfur are also provided

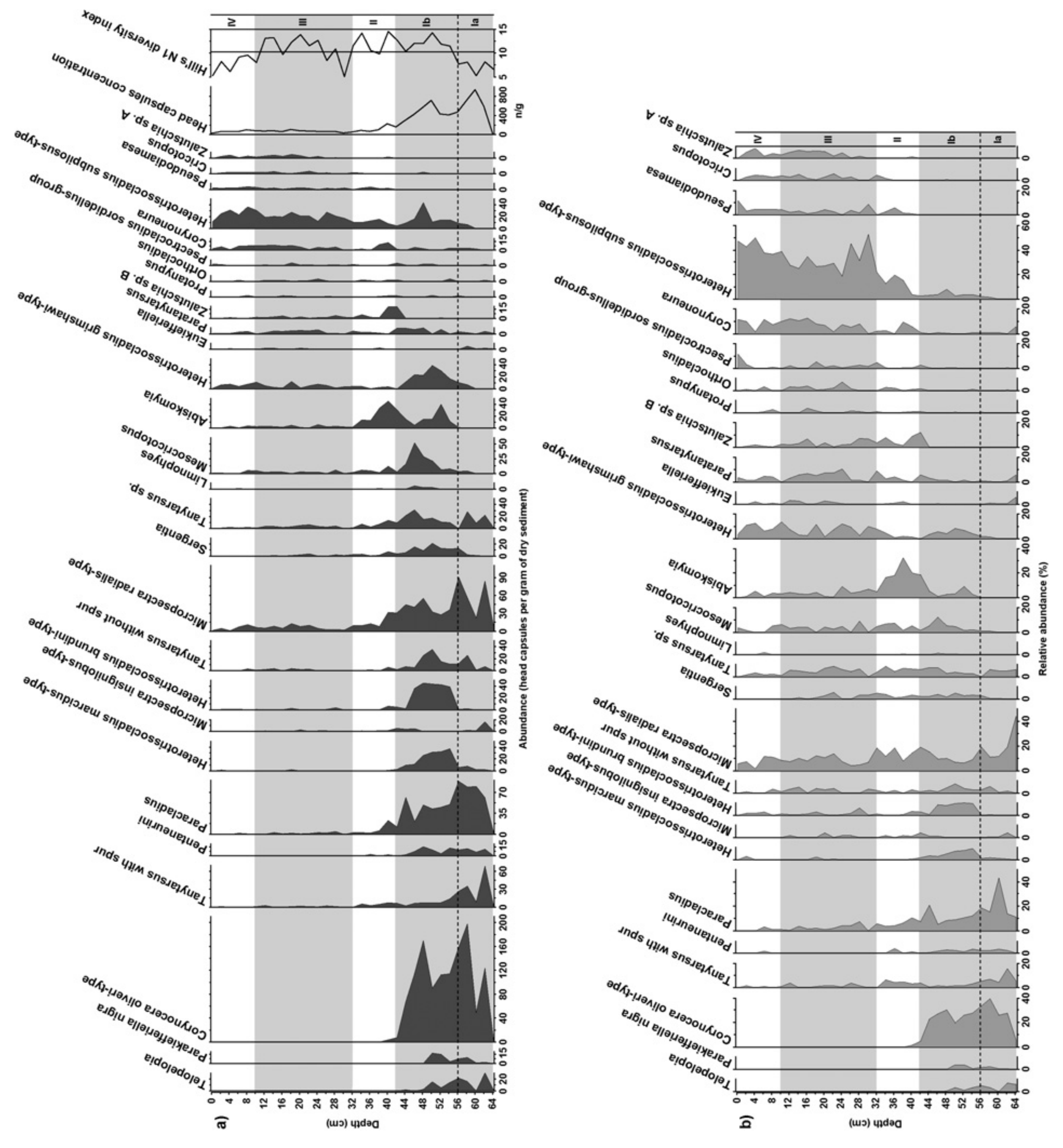

Figure 5 Chironomid stratigraphies in abundance per gram of dry sediment (a) and in relative abundance (b) of the sediment core 4P of Caribou Lake. Head-capsule concentration and Hill's N1 diversity index are also provided. The inferred August air temperatures were developed with a calibration data set from the northern part of Québec (Larocque *et al.*, 2006). Zones were calculated by a CONISS cluster analysis

(nitrogen) to the lake. Between 42 and 32 cm, both total carbon and nitrogen decreased without having any impact on the C_{Tot}/N ratio. Starting at 32 cm, nitrogen increased and stabilized in the upper part of the core around a mean value of 0.75%, with only a short-lived increase between 10 and 5 cm. By contrast, the total carbon content showed much more variability during that same period, also affecting the C_{Tot}/N ratio. The sulfur content, which is related to lake productivity and biodegradation (Wetzel, 2001), was higher between 64 and 46 cm and then decreased and stabilized in the top part of the core. The LOI followed the same fluctuations as observed in the C_{Tot}/N ratio and remained stable throughout the lake's history.

Midges

Four different stratigraphic zones were obtained using the program ZONE (Figure 5). The same zones were obtained with the concentration (Figure 5a) and the relative abundance (%) data (Figure 5b). Both stratigraphies providing similar information, the concentration diagram will be mainly discussed, unless there are discrepancies between the two graphs.

Results of the DCA analysis are presented on Figure 6. The first axis of the DCA explained 79.3% of the variance in the chironomid assemblages while DCA axis 2 explained 11.6% of the variance.

Zone I

This zone was visually divided into two phases: 64–56 cm (Ia), and 56–42 cm (Ib). The first phase corresponded to the establishment of the lake invertebrate community and was dominated by *Corynocera oliveri*-type, *Paracladius* and *Microspectra radialis*-type. *C. oliveri*-type, a cold-littoral zone dweller, was also found to be abundant during the colonization phase of lakes in the southern

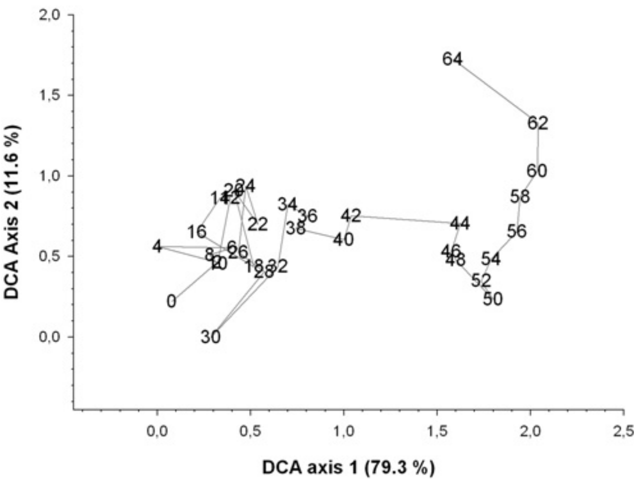

Figure 6 Amount of chironomid assemblage turnover as estimated by a Detrended Correspondence Analysis (DCA)

Alps, France (Gandouin and Franquet, 2002), Norway (Brooks and Birks, 2000; Velle *et al.*, 2005), Scotland (Brooks *et al.*, 1997), and Sweden (Larocque and Bigler, 2004). Based on previous inference models (eg, Larocque *et al.*, 2001, 2006), *C. oliveri*-type is a cold-stenotherm with a temperature optimum around 10–11°C. *Paracladius* and *M. radialis*-type were found in the bottom core section of many lakes such as a small Swiss subalpine lake (Heiri *et al.*, 2003) and *Paracladius* commonly occurs in deep and cold arctic tundra lakes (Walker *et al.*, 1997, 2003). Hill's N1 diversity indices (Figure 5a) for this phase were lower than 10, but the concentration of chironomid head capsules reached a maximum of ~ 900 head capsules per gram dry sediment.

The second phase was characterized by a rapid increase of Hill's N1 diversity indices with the appearance of the genus *Abiskomyia*, a cold-adapted taxon usually found in shallow arctic lakes and flowing waters (Oliver and Roussel, 1983; Walker, 1990; Olander *et al.*, 1999); *Mesocricotopus*, a taxon of deep, cold and well-oxygenated arctic tundra lakes (Walker *et al.*, 2003); *Sergentia,* a profundal taxon (Francis, 2001); and the *Heterotrissocladius* group, which are adapted to cold waters (Olander *et al.*, 1999) of oligotrophic lakes (Walker and Paterson, 1983). *H. marcidus*-group and *H. brundini*-group had high concentrations but percentages below 20% in this phase. Their peaks were coincident with decreases of the taxa that first colonized the lake, in particular *C. oliveri*-type. The cold stenotherm (Brooks and Birks, 2001) and acidophilic (Pinder and Morley, 1995) taxa belonging to the *H. grimshawi*-group also reached their maximum abundance during the *C. oliveri*-type decline. This shift also corresponded to an increase of *Parakiefferiella nigra,* a taxon generally related to deep oxygenated lakes (Walker and Mathewes, 1989; Quinlan *et al.*, 1998), and to increases of *Cricotopus* and *Limnophyes*, which are widely distributed in the shallow littoral zones of lakes and on aquatic plants (Oliver and Roussel, 1983). Abundances of initially dominant taxa decreased (*Paracladius* and *M. radialis*-type) or completely (*C. oliveri*-type) disappeared at 42 cm. The

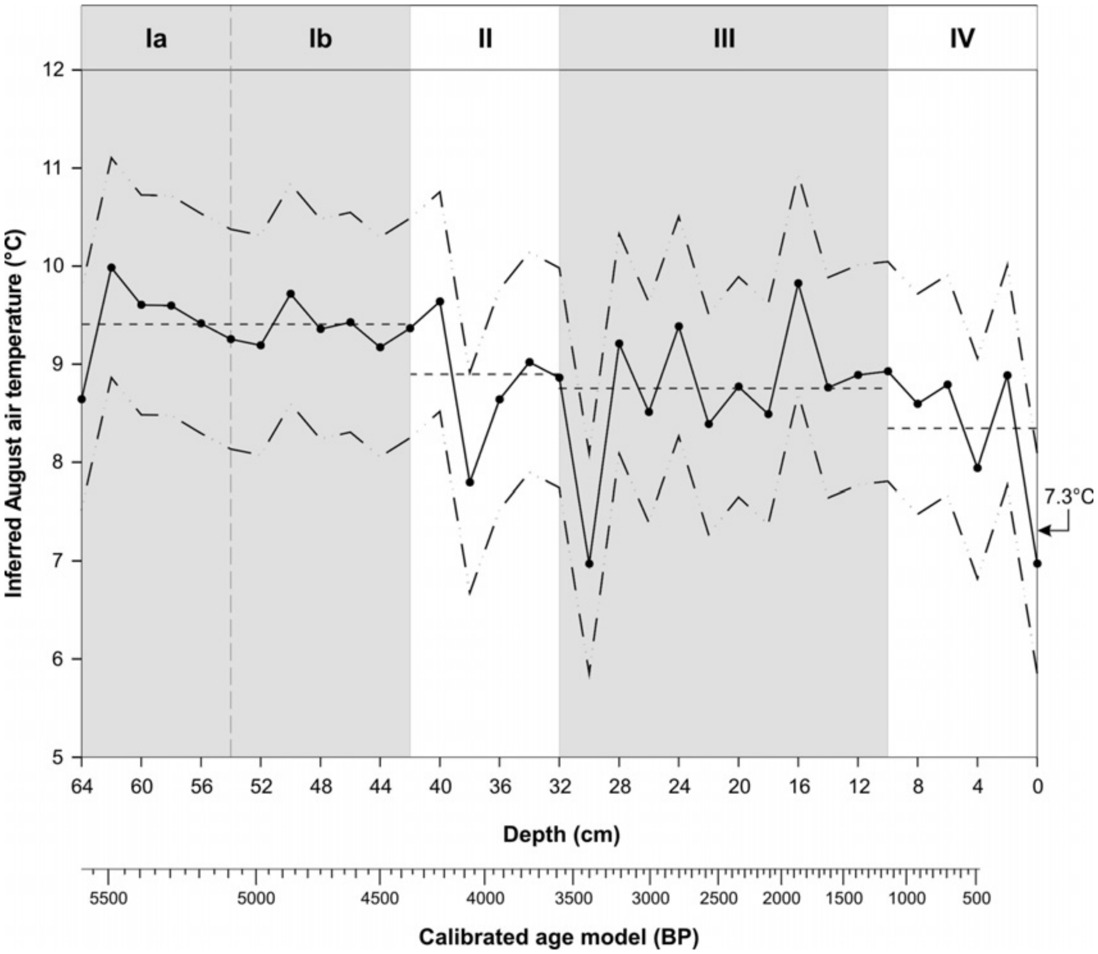

Figure 7 Chironomid-based August air temperature (°C). The model root mean square error of prediction (RMSEP) is represented along the profile. The mean inferred temperature for each chironomid-based zone is represented as well as the climate normal (1971–2000) in August at Coral Harbour (7.3°C)

changes in percentages of *M. radialis*-type were less obvious than its changes in abundance. The head-capsule concentrations decreased to ~ 200 per gram dry sediment.

The DCA scores for the first axis (Figure 6) were higher during this zone than in any other zone, suggesting unstable lake conditions (Bigler *et al.*, 2002).

Zone II

This zone was dominated by *Abiskomyia*, a change that is more obvious in the relative abundance (%) diagram. *Pseudodiamesa*, a cold water, high arctic taxon (Walker *et al.*, 1997; Larocque *et al.*, 2006) and often associated with flowing waters (Oliver and Roussel, 1983), appeared with *Zalutschia* sp. B. Both taxa belonging to *Zalutschia* are generally encountered in dystrophic humic waters (Walker *et al.*, 1991) and in productive anoxic environments (*Z.* sp. A; Quinlan and Smol, 2001). *Corynoneura* percentages increased during this zone, as well as *Heterotrissocladius subpilosus*-group. The head-capsule concentrations decreased to ~ 50 head capsules per gram dry sediment at 32 cm. The DCA scores for the first axis (Figure 6) steadily decreased up to 32 cm core depth.

Zone III

This zone is characterized by increased abundance and relative abundances (%) of the *H. subpilosus*-group, which dominated the assemblages together with *Corynoneura*, *H. grimshawi*-group and *M. radialis*-type. The beginning of this zone (30 cm) was marked by a rapid decline of the Hill's N1 diversity index and of the head-capsule concentration. Starting at 28 cm, these variables returned to their initial values (Hill's N1 index around 10 and head-capsule concentrations around 50 head-capsules per gram dry sediment) and thereafter did not show major variations, except at 16 cm, where they both dropped sharply. *Cricotopus* and *Zalutschia* sp. A were present throughout the whole period. Percentages of *H. grimshawi*-group slightly increased compared with the previous zone. The DCA scores were relatively stable during that zone.

Zone IV

The chironomid assemblages of this zone were much the same as those encountered in zone III, for they only differed by a higher abundance of *H. subpilosus*-group and the disappearance of Pentaneurini and *Paracladius*. *Psectrocladius sordidellus*-group and *Pseudodiamesa* increased in the top sample. This zone was also characterized by a constant decline of Hill's N1 diversity index, with the possible extinction of less abundant taxa such as *Sergentia* and *Paracladius*. DCA scores ranged between 0 and 0.5.

Temperature reconstruction

The chironomid-based August air temperature (°C) profile is presented on Figure 7. All samples had a good fit to temperature, more than 85% of the fossil taxa were found in the training set and all samples had good modern analogue situations, suggesting that the temperature optima should be accurate. The climate normal (1971–2000) in August at Coral Harbour is 7.3°C while the inferred temperature in the uppermost sample was 7°C, suggesting that the inference was quite reliable.

Zone I was separated into two phases, as described above. The inferred August air temperature rose rapidly to a maximum of 10°C, and then decreased to ~ 9.5°C. The inferred temperatures for the second phase stabilized at ~ 9.5°C. In zone II, the inferred temperature was, in average, 8.7°C. This average was pulled down by one cold oscillation (7.8°C) at 38 cm (about 4200 cal. yr BP). In zone III, inferred August air temperatures remained relatively stable at ~ 8.6°C in average, except for a short-lived peak of ~ 10°C at 16 cm (about 1900 cal. yr BP). In the last zone, the average temperature was 8.3°C, with the coldest temperature (7.3°C) recorded in the uppermost sample. The amplitude of average temperature changes between zone I and zone IV was of 1.2°C, which is slightly above the RMSEP. The variation between the warmest (10°C) and the coldest inferences (7.3°C) was 2.7°C.

Discussion

Following the retreat of the Laurentide Ice Sheet around 6600–6900 cal. yr BP (Dredge, 2001; Rouault, 2006), glacio-isostatic land uplift raised the northern part of Southampton Island, which in the Caribou Lake area was still inundated by marine waters. The shift from a marine to a lacustrine environment occurred at about 5570 cal. yr BP according to our age model and revealed by the presence of dense, clay-rich marine sediments at the bottom of the core. This event also corresponded to an almost instantaneous increase of the sediment porosity and to a rapid decline of the Ca and, to a lesser extent, K concentrations.

Holocene environmental change at Caribou Lake

During the lacustrine phase, the fine grain-size distribution indicates deposition environments of low energy, with little direct influence from the single tributary. These conditions proved to be quite stable during the last 5570 cal. yr.

Both chironomid-assemblage and DCA data reflect the highly variable environmental conditions between about 5570 and 4360 cal. yr BP and their relative stability after about 3570 cal. yr BP. This is also supported by the major chemical elements (Figure 3) and the density of the sediment, which varied in the first and second zones but stabilized afterwards. Following the creation of the lake, rapid appearances of some chironomid taxa proved their capacity to rapidly colonize lakes on unstable, recently deglaciated landscapes. This instability found its expression in a pre-establishment period (phase one, zone Ia, 64–56 cm) characterized by the highest fossil head-capsule concentrations and by the highest DCA values in the entire core. The dominance of common cold-stenotherm littoral or deep water taxa, such as *Corynocera oliveri*-type, *Paracladius* and *Microspectra radialis*-type resembles situations recorded from many cores corresponding to early postdeglaciation events (eg, Heiri *et al.*, 2003; Larocque and Bigler, 2004). This period early in the lake's history is usually described as extremely unstable owing to profound modifications of the limnological and landscape states (Korhola *et al.*, 2002; Saulnier-Talbot *et al.*, 2003). Density differences between fresh and saline waters may also have contributed to this instability and created a meromictic-like system shortly after the creation of the lake. Higher salinity in the bottom part of the lake resulting from trapped seawater might be an explanation for the lower diversity of profundal taxa during this phase, especially at 64–60 cm. However, the most abundant profundal taxa found in this section (*Paracladius* and *Micropsectra radialis*-type) have never previously been associated with saline environments (Walker *et al.*, 1995) but rather with deep and cold arctic tundra lakes (Walker *et al.*, 1997; Pellatt *et al.*, 1998; Brooks and Birks, 2000; Gandouin and Franquet, 2002).

This pre-establishment period was short-lived and was followed in the second phase (zone Ib, 56–42 cm) by the appearance of many new chironomid taxa that may have spread in all the newly available lake habitats The appearance of cold-adapted taxon *Abiskomyia*, usually encountered in the shallow zones of arctic lakes (Oliver and Roussel, 1983), supports this hypothesis. To a lesser extent than in the first phase, chironomid assemblages were still highly variable, as expressed by the first DCA axis.

Chironomid assemblages in the second zone of the core (42–32 cm) portrayed a stabilization of the lake ecosystem. The disappearance of almost all the littoral and deep profundal taxa corresponded to a distinct decrease in the scores of the first DCA axis.

The two uppermost zones of the core covered the last 3500 cal. yr BP and clearly reflected cold oligotrophic conditions, with the dominant taxon belonging to *Heterotrissocladius subpilosus*-group. This period was likely the more stable in the lake's history, with a constant decrease in the chironomid assemblages' variability (DCA, Figure 6). This relative stability in the chironomid assemblages only changed in the uppermost few centimetres of the core, also shown in changes in the density and some major chemical elements.

Temperature reconstruction and comparison with regional palaeoclimatic data

Inferred Holocene August air temperatures at Caribou Lake ranged from 10.0 to 7.0°C, with the highest inferred values associated with the early lake stages (about 5570–4360 cal. yr BP) and an obviously more stable period spanning from about 3570 cal. yr BP until the present day. The new inference model used to reconstruct air temperatures in this study covered a large geographical and climatic gradient, from southern Québec (Mont-Laurier) to Southampton Island (Larocque *et al.*, 2006). However, this model is lacking mid- and high-arctic lakes, which might have reduced its performance on our samples. Also, as described by Larocque and Hall (2004), the large root mean square error of prediction (RMSEP) of the model used for this study (RMSEP = 1.12°C) might limit our interpretation of low (< 1°C) amplitude temperature variations, although it has been shown that small changes in the range of 0.5°C can be adequately inferred by chironomids (Larocque and Hall, 2003), and that the RMSEP are generally overconservative and that the average difference between meteorological data and chironomid-inferred temperatures is smaller than 0.7°C (I. Larocque, unpublished data). A regional comparison with other lakes is usually used to decrease this uncertainty. However, since our study is the first of its kind completed on this island, we can only refer to data from other study sites located far from Caribou Lake. Despite these restrictions, we can ascertain that our temperature reconstructions are in close agreement with results reported from previous palaeolimnological studies in northern Québec and Labrador (Pienitz *et al.*, 2004b). Based on the inference model developed by Walker *et al.* (1997), Fallu *et al.* (2005) inferred surface water temperatures derived from chironomid remains of a shrub-tundra lake in northern Québec. This lake experienced relatively stable palaeoclimatic conditions between 4900 and 1500 cal. yr BP. Using terrestrial pollen remains, Sawada *et al.* (1999) inferred stable August air temperature throughout the Holocene at four lake sites (LR1, LB1, BI2, GB2) in northwestern Québec. In the same study, between 5700 to 2000 cal. yr BP, they obtained similar temperature patterns for the sea surface temperatures in the southern James Bay area using marine dinocysts. Apart from temperature reconstructions, many studies have already shown this stability during the Holocene. Ponader *et al.* (2002) studied the fossil diatom assemblages during the late Holocene (last 3000 cal. yr BP) in a subarctic lake in northwestern Québec. The continued dominance of the taxon *Fragilaria virescens* var. *exigua* confirmed the stable limnological conditions (including dissolved organic carbon content) that prevailed during that time.

In the northern Québec, Labrador and Baffin Island regions, the Holocene Thermal Maximum (HTM) was delayed by thousands of years with respect to the early Holocene insolation maximum because of the late decay of Laurentide Ice Sheet remnants (Williams *et al.*, 1995). Quantitative multiproxy studies estimated that the HTM occurred in these regions between 6300 and 3700 cal. yr BP (Kaufman *et al.*, 2004). This period, warmer than today by about 1–2°C (Kaufman *et al.*, 2004), coincided with changes in vegetation density and a northern advance of the arctic tree line (Payette and Lavoie, 1994). Our results suggest that the HTM in the northern Southampton Island–southern Foxe Basin region ended around 4400 cal. yr BP and that August air temperatures (9.5°C on average) were about 2.2°C higher than today's climate normal (7.3°C). The average temperature over the last 1000 cal. yr BP was, on average, 1.2°C colder than before *c.* 4400 cal. yr BP. The grain-size analysis revealed that the proportion of clay (0–10 μm) particles increased up the core, with the highest values obtained near the water/sediment interface. Cold conditions usually increase the relative proportion of clay because of no high discharge from the watershed. The sedimentological data thus support the temperature reconstruction using chironomids, with colder inferences during the last 1000 cal. yr BP.

Chironomid dating

Lake-sediment chronologies are commonly based on AMS ^{14}C radiocarbon dating of plant macrofossils. However, in the unproductive watersheds of arctic tundra lakes with their sparse vegetation cover and thin soils, alternative dating methods must be considered (reviewed in Wolfe *et al.*, 2004), such as humic-acids extracted from bulk sediment and chironomid head capsules. This latter method, which yielded consistently younger ages in Fallu *et al.* (2004), proved to be more reliable compared with bulk sediment dating at Lake K2 in arctic Québec. In our study, two dates at different levels in the core were older, with differences of more than 3000 years, compared with the dates derived from humic-acids and a marine shell. More than 1200 head capsules were used for each dating. As shown in the stratigraphic diagram (Figure 5), these chironomid remains were mainly composed of large head capsules of *Corynocera oliveri*-type, *Paracladius* and, to a lesser extent, *Microspectra radialis*-type. Although the samples were pre-treated with acid/alkali/acid (44.5–45.5 cm), and acid washes (62 cm), contamination through old carbon trapped inside their capsules could have caused this bias. The chironomid AMS ^{14}C dating method therefore needs further testing and refining in order to evaluate its efficiency in such situations.

Conclusions and perspectives

Palaeoenvironmental reconstructions from Caribou Lake on northeastern Southampton Island showed consistent trends in the different proxies used: unstable conditions after the sea retreated from this site, with inferred temperatures warmer by 2°C compared with today's climate normal, followed by more stable environments and a slight decrease (within the model's RMSEP) of average temperature during the last 1000 cal. yr BP. This study, which was mainly based on fossil chironomid interpretations, was supported by sedimentological analyses. No sign of warming was recorded at that site, which is consistent with reconstructions further south in Quebec, but contrasts with reconstructions obtained from the higher arctic. This reconstruction suggests that Southampton Island has not yet responded to climate change. In the future, more palaeolimnological studies will have to be initiated in the Foxe Basin region to improve our knowledge of past climates and environments in this area and strengthen our interpretations.

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