

Vegetation and climate of the last interglacial on Baffin Island, Arctic Canada

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Received 30 September 2004; accepted 11 November 2005

Abstract

Sediment cores recovered from three mid-arctic lakes on Cumberland Peninsula, eastern Baffin Island, Arctic Canada, contained two units of unconformably superimposed organic sediment (gyttja), the upper of which represented sedimentation during the Holocene. Radiocarbon ages on aquatic macrofossils from the lower gyttja suggested it to be >50 ka BP, while luminescence ages from two cores constrained the age of this sediment to >90 and <130 ka BP, that is, encompassing the last interglacial. Pollen spectra from these cores were used to reconstruct past vegetation and climate of the Holocene and last interglacial. In each core, last interglacial sediments yielded remarkably high pollen concentrations, and included far greater percentages of shrub (*Betula* and *Alnus*) pollen grains than did overlying Holocene sediments. Numerical comparisons of fossil pollen assemblages to a data set of 400 modern high-latitude lake sediment samples revealed that the last interglacial vegetation of east-central Baffin Island was Low Arctic in character, comparable to present-day southwest Greenland. From applications of both correspondence analysis regression and best modern analogue methodologies, we infer July air temperatures of the last interglacial to have been 4 to 5 °C warmer than present on eastern Baffin Island, which was warmer than any interval within the Holocene. On these grounds, we ascribe the lower lacustrine unit in these lakes to the climatic optimum of the last interglacial, ca. 117 to 130 ka BP (Marine Isotopic Stage 5e).

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Keywords: Arctic; Pollen; Last interglacial; Paleoclimate; Baffin Island

1. Introduction

The Arctic is both highly responsive to climate variability, and directly involved in several key processes that mediate climate change. Consequently,

there is a need to refine our understanding of arctic climate dynamics, including a quantitative assessment of past intervals of relative warmth. Pollen grains preserved in lake sediments are a useful proxy for reconstructing vegetation and climate. Lakes situated at sensitive ecotonal boundaries, such as the Low to Mid Arctic bioclimatic zone, are of particular interest because small changes in climate can induce relatively

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large vegetational changes that are discernible in the pollen record (e.g., Barbour et al., 1998).

The last interglacial period *sensu lato* (Marine Isotope Stage 5; MIS 5), 75–130 ka before present, is considered an interval of relative warmth throughout the circum-Arctic region. A compilation of qualitative climate proxies from deep-sea sediments, ice cores, and terrestrial near-shore sequences (LIGA members, 1991) revealed conditions about 4 °C warmer than present in northeastern Canada and Greenland for the early warmest portions of the last interglacial (*sensu stricto*), ca. 115–130 ka BP (MIS 5e). Plant macrofossil and fossil insects from east-central Greenland indicate that mean summer air temperatures were about 5 °C above present (Bennike and Böcher, 1994). The NorthGrip ice core in Greenland reveals the most detailed arctic climate history for the last interglacial, indicating mean annual temperatures 5 °C warmer than present (NGRIP members, 2004). A quantitative pollen-based climate reconstruction from Bol'shoi Lyakhovskiy Island in the Laptev Sea (Siberia), suggests that mean July air temperatures were 4 to 5 °C higher than present during the Eemian climatic

optimum (Andreev et al., 2004a). However, similar analyses are currently lacking for the eastern Canadian Arctic.

Over the last decade, pre-Holocene lacustrine sediments have been raised from a number of lakes on Baffin Island, Arctic Canada (Wolfe and Härtling, 1996; Steig et al., 1998; Miller et al., 1999; Wolfe et al., 2000). Although a handful of studies have qualitatively addressed the climate of Baffin Island during the last interglacial using pollen, diatoms, and sediment lithostratigraphy (Miller et al., 1977, 1999; Wolfe et al., 2000), the present investigation is a first attempt to quantitatively reconstruct last interglacial July air temperatures for this region. We report detailed last interglacial pollen records from three lakes on Cumberland Peninsula, eastern Baffin Island, situated close to the Low–Mid Arctic ecotonal boundary. We then compare Holocene and last interglacial vegetation and climate histories, revealing that a northward expansion of Low Arctic vegetation occurred over the Cumberland Peninsula during the last interglacial, but was not repeated at any time in the Holocene.

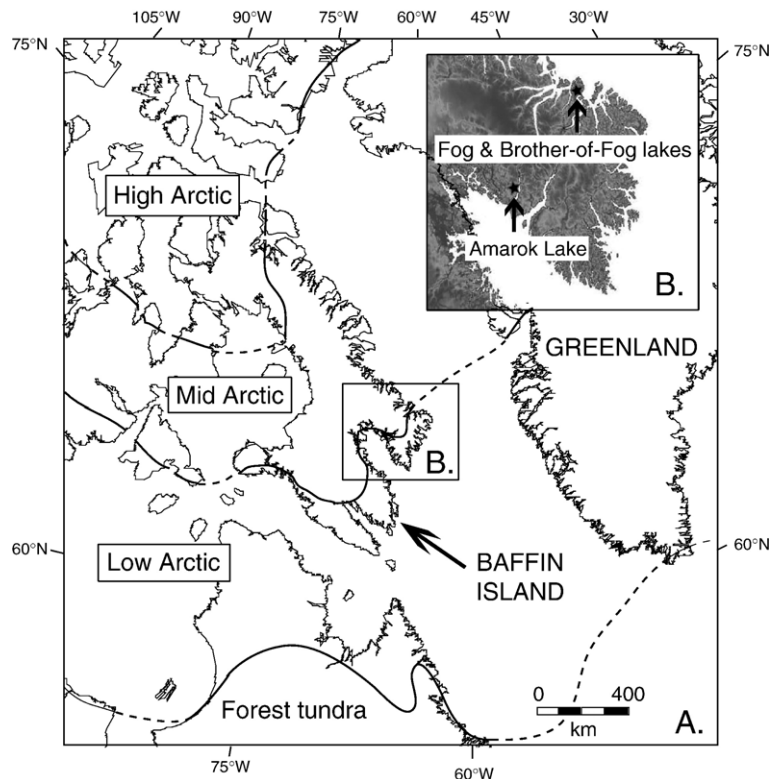


Fig. 1. Locations of the study lakes on northern Cumberland Peninsula, Baffin Island, and approximate limits of Low, Middle, and High Arctic vegetation zones after Young (1971).

2. Study area

Several small upland lakes on Cumberland Peninsula (Baffin Island, Nunavut Territory, Canada) contain weakly-stratified, organic-rich lacustrine sediments that underlie Holocene gyttja, and are at or beyond the range of radiocarbon dating (Wolfe, 1994; Steig et al., 1998; Wolfe et al., 2000; Miller et al., 2002; Wolfe et al., 2004). The two organic (gyttja) units are commonly, but not universally, separated by more strongly stratified and dominantly minerogenic sediments. Cores from three of these lakes (Fig. 1) were selected for pollen analysis based on the overall length and quality of their pre-Holocene organic sediments. Amarok Lake (66°16' N, 65°45'W, 848 m altitude, 700 m×100 m, 14.5 m water depth at coring site) is on southwestern Cumberland Peninsula immediately north of Pangnirtung Fiord. Fog Lake (67°11'N, 63°15'W, 460 m altitude, ca. 170×140 m, 9.5 m water depth at coring site) and neighbouring Brother-of-Fog Lake 11 km to the northwest (67°11.5'N; 63°08'W; 360 m altitude, ca. 350×500 m, 16.0 m water depth at coring site), are situated on the peninsula between Kangert and Padle fiords on northern Cumberland Peninsula, about 145 km from Amarok Lake (Fig. 1).

The nearest community to Amarok Lake, Pangnirtung, has a mean annual air temperature of -8.9 °C (July mean: 7.5 °C; January mean: -26.3 °C), and a mean annual precipitation of 396 mm, of which 56% falls as snow (Maxwell, 1980). Because of its altitude, Amarok Lake experiences colder and moister conditions, and consequently the vegetation around the lake is limited to a sparse *Cassiope tetragona*–*Salix*–lichen tundra. *Betula* is locally absent. The estimated mean July air temperature at Amarok lake is approximately 5 – 6 °C.

The climate of northern Cumberland Peninsula is more severe. At Broughton Island (North Warming Station Fox 5; 67°32'N, 63°47'W, 584 m altitude), 40 km northwest of Fog and Brother-of-Fog lakes, mean annual air temperature is -11.8 °C (July mean: 4.4 °C; January mean: -24.8 °C), and mean annual precipitation is 262 mm, 85% falling as snow. Precipitation

increases dramatically eastward along the coast so that at Cape Dyer (66°34'N, 61°37'W, 393 m altitude), 100 km east of the lakes, mean annual precipitation is 603 mm (94% as snow, mean annual air temperature: -11.0 °C; July mean: 5.3 °C; January mean: -24.2 °C) (Environment Canada, 2004). Vegetation around Fog and Brother-of-Fog lakes is typical of the Middle Arctic Zone (Young, 1971), with sparse vascular plant cover and few woody taxa. *Betula* is currently absent from the local vegetation. However, at the heads of Padle and Kangert fiords, 50 km to the west of the lakes, isolated outlier populations of prostrate dwarf birches (*Betula nana*, *B. glandulosa*) occur in the valley floor. Green alder (*Alnus crispa*) does not occur on Baffin Island today, nor does it appear to have at any time in the Holocene. We estimate mean July air temperature at Fog and Brother-of-Fog lakes to be similar to the one at Broughton Island, which is 4 to 5 °C.

3. Methods

3.1. Sediment coring and chronology

The three lake sediment cores (7 cm diameter) were obtained in May of 1996 and 1998 from lake ice using a sledge-mounted percussion coring system capable of penetrating dense inorganic sediments (Nesje, 1992). Whole-core magnetic susceptibility (MS) was measured with a portable Bartington loop in the field and again prior to core splitting, logging, and sub-sampling in the laboratory.

The geochronology of Fog Lake sediments was discussed by Wolfe et al. (2000), that of Brother-of-Fog Lake by Miller et al. (2002), and that of Amarok Lake by Wolfe (1996). However, many of these results were provisional and are supplemented by data reported here. For accelerator mass spectrometry (AMS) ^{14}C dates, we targeted either bryophyte macrofossils (principally *Warnstorfia exannulata* leaves and stems), or sediment humic acid extracts. Miller et al. (1999) demonstrated that the average ^{14}C activity of mosses living in non-carbonate Baffin Island lakes was indistinguishable

Table 1
AMS ^{14}C dates pertaining to the lower organic units of the cores investigated here

Core	Depth (cm)	Unit	^{14}C ages (yr BP)	Lab number	Material
98AKL-02	124–125	A-I	38,600±280	OS-17676	Humic acid extract
98AKL-02	124–125	A-I	46,000±640	OS-18067	Bryophyte macrofossil
98AKL-02	170–171	A-I	47,900±780	OS-18066	Bryophyte macrofossil
96FOG-05	110.0–111.5	F-III	>44,400	CAMS-31808	Humic acid extract
96FOG-05	110.0–111.5	F-III	>52,200	CAMS-28652	Bryophyte macrofossil
98BRO-05	134.5–135.5	B-III	60,000±1900	OS-18064	Bryophyte macrofossil

from that of the contemporary atmosphere, implying atmospheric equilibration with respect to carbon and suitability for ^{14}C dating. The accuracy of humic acid dates in this region depends principally on sources of ancient dissolved organic carbon in lake catchments (Wolfe et al., 2004).

However, because the lower gyttja in these lakes has proven close to, or beyond, the interpretable range of AMS ^{14}C dates (Table 1), we also applied luminescence dating of the fine-grain polymineral fraction to estimate the age of these sediments in Fog and Brother-of-Fog lakes. In Fog Lake, sections of ^{14}C -dated Holocene gyttja were also dated by luminescence to verify the completeness of solar resetting of minerals present in organic-rich sediments.

3.2. Pollen analysis

The cores (Amarok Lake, 205 cm; Fog Lake, 137 cm; and Brother-of-Fog Lake, 187 cm) were subsampled at intervals ranging from 0.5 to 10 cm, with the densest sampling applied to the lower organic sediments. This resulted in 71, 49, and 27 pollen samples from Fog, Amarok and Brother-of-Fog lakes, respectively. Holocene sediments were not analyzed from Brother-of-Fog Lake. From each level, 2.0 cm³ of fresh sediment were processed for pollen using standard techniques including dispersion with KOH, digestion with HF and HCl, and acetolysis (Faegri and Iversen, 1975). Residues were stained with fuschin, mounted in glycerine, and examined microscopically at 400 \times and 1000 \times . Pollen concentrations were determined by spiking with *Eucalyptus* pollen grains prior to processing (Benninghoff, 1962). The basic sum used for relative frequency calculations included all spermatophyte taxa. Although pteridophyte spores were excluded from the basic sum, their representations were expressed as relative frequencies in relation to the basic sum. Pollen and spores were identified with reference to the keys of Richard (1970), McAndrews et al. (1973), and Moore et al. (1991), as well as modern pollen slides archived at the Laboratoire Jacques-Rousseau, Université de Montréal.

The palynological richness of fossil samples was estimated by means of rarefaction analysis (Birks and Line, 1992), using the 3Pbase software (Guiot and Goeury, 1996). Rarefaction analysis provides unbiased estimates of taxonomic richness for a standardized sample size (i.e. grain count), using a random selection without replacement strategy. The method produces robust estimates of the expected number of taxa ($E(T_n)$) for the smallest pollen sum (n) in the studied sequence.

Rarefaction analysis was performed on the raw counts of total assemblages, including both spermatophyte and pteridophyte taxa.

The equatorial diameter of *Betula* pollen grains was measured systematically in order to ascertain whether they originated from shrub or tree species involved (Birks, 1968; Richard, 1970; Prentice, 1981; Mäkelä, 1996; Caseldine, 2001). Diameters were measured in polar view as the distance between the outer layer of the exine and the bottom of the opposite pore. For most samples, at least 100 non-folded *Betula* grains were measured. Because glycerine-mounted slides induce swelling of pollen grains (Andersen, 1978), these measurements were done as soon as possible following sample preparation (i.e., within one month). For reference, *Betula* pollen from surface sediments of a lake surrounded by luxuriant populations of *B. nana* and *B. glandulosa* had diameters in the 17–21 μm range.

3.3. Paleoclimate reconstruction

3.3.1. Modern pollen database

In North America and Greenland, modern pollen assemblages from Low Arctic shrub tundra are typically dominated by *Betula*, Ericales, *Alnus*, *Picea* and *Pinus* (Ritchie and Lichti-Federovitch, 1967; Fredskild, 1973; Richard, 1981; Fredskild, 1983; Short et al., 1985; Fredskild, 1992; Gajewski et al., 1993, 2000; Kerwin et al., 2004). In the eastern Canadian Arctic, the latter three taxa are exotic and thus represent long-distance wind-borne transport from southern source areas. However, shrub *Alnus* currently grows in south-western Greenland, north-western and north-central Canada, and on the Alaskan north slope (Ritchie et al., 1987; Fredskild, 1996; Oswald et al., 2003). Middle Arctic herb tundra vegetation is characterized by Ericales, Cyperaceae and *Salix* (Ritchie and Lichti-Federovitch, 1967; Fredskild, 1973; Richard, 1981; Fredskild, 1983, 1985; Short et al., 1985; Gajewski, 2002; Kerwin et al., 2004). Sparser high arctic herb tundra and polar desert are characterized by Poaceae, *Salix* and minor contributions from diverse herb pollen such as Caryophyllaceae, Papaveraceae, Ranunculaceae and Saxifragaceae (Fredskild, 1973; Hyvärinen, 1985; Short et al., 1985; Gajewski, 1995; Gajewski and Frappier, 2001; Gajewski, 2002; Kerwin et al., 2004).

Although these relationships have been known for some time, they have not been formalized adequately for paleoclimatic reconstructions of the last interglacial on Baffin Island. To this end, modern pollen assemblages from 400 sites north of 50°N latitude were collated, representing north-western Canada ($n=120$), northern

Québec ($n=94$), the Canadian Arctic Archipelago ($n=128$), and Greenland ($n=58$). This provided a new modern pollen database restricted entirely to lake surface sediments. Raw data originated from both published (Fredskild, 1973; Ritchie, 1974; Richard, 1979; Richard, 1981; Fredskild, 1983; Fredskild, 1985; MacDonald and Ritchie, 1986; Ritchie et al., 1987; Gajewski, 1991; Richard et al., 1991; Sandgren and Fredskild, 1991; Fredskild, 1992; Kerwin, 2000; Gajewski, 2002; Kerwin et al., 2004) and unpublished sources (B. Fréchette; B. Fredskild; J.C. Ritchie).

Among the 159 pollen taxa reported by these authors, several taxonomic groups were harmonized to ensure a standardized and consistent taxonomic resolution. This resulted in a sub-total of 63 taxa. Thereafter, all taxa that never exceeded 1% of the sum in any one sample were also omitted, resulting in the final inclusion of 34 taxa in the modern database (Table 2). These taxa may all be unambiguously associated with fossil representatives preserved in lake sediments.

Ideally, when using pollen data for paleoclimatic inferences, one assumes that most of the observed pollen originates from plants living in proximity to the lake. However, exotic wind-blown pollen produced by boreal taxa are consistently, and at times strongly, registered in arctic assemblages in proportions that are functions of both the distance from the source and the degree of dilution by locally-produced pollen. Because both of

these factors potentially relate to climate, exotic taxa were included in the modern database. Furthermore, for the crucial taxa *Betula* and *Alnus*, it is difficult to differentiate palynologically the local presence of scattered individuals from dense distant populations.

3.3.2. Climate interpolations for the modern reference sites

A major hindrance to developing a pollen database for paleoclimatic reconstructions is obtaining meaningful estimates of climatic parameters to associate with individual modern pollen samples. This problem is exacerbated in the Arctic, where meteorological stations are few. For this study, climatic parameters for the 400 sites were estimated by weighted-averaging of the closest available meteorological station data, using 3Pbase software (Guiot and Goeury, 1996). Modern climate parameters at the three fossil sites were also estimated this way. The interpolated climatic data originated from averaged measurements at a total of 400 meteorological stations in Alberta ($n=146$), Yukon ($n=19$), NWT and Nunavut ($n=52$), Ontario ($n=68$), Newfoundland ($n=12$), Québec ($n=79$), and Greenland ($n=24$) (Cappelen et al., 2001; Environment Canada, 2004). The data sets included thirty year averages of climate measurements. Climate observations of the period 1971–2000 were used for most of the stations ($n=361$). The period 1961–1990 was used for the remainder ($n=39$). The duration of these climatic records was directly comparable to the time represented by the surface sediments (typically 0–1 cm) collected from northern lakes, given that low sediment accumulations rates were the norm (Wolfe et al., 2004). Moreover, multi-decadal integrations of both climatic and biological data reduced the effects of short-term variability within both systems, allowing for the reconstruction of average conditions from sediment sample that, similarly, represent several decades of accumulation. The estimated climatic parameter, c_o , for a modern pollen site, o , was given by the weighted-average of all the meteorological stations, k , at a distance, d_{ok} , less than or equal to a radius of 10° , R , from the site (Guiot, 1987), as given by:

$$c_o = \left(\sum_k c_k / d_{ok}^2 \right) / \left(\sum_k 1 / d_{ok}^2 \right)$$

and

$$d_{ok}^2 = (x_o - x_k)^2 + (y_o - y_k)^2$$

where x_k , y_k and c_k represent the longitude, latitude, and measured climatic variables at each meteorological station, $k=1$ to m ($m=400$), respectively. The robustness

Table 2

Pollen taxa retained in the modern database for paleoclimate reconstructions

Woody plants	Herbs
<i>Abies</i> *	<i>Ambrosia</i> *
<i>Betula</i>	Apiaceae*
Cupressaceae*	<i>Artemisia</i>
<i>Larix</i> *	Brassicaceae
<i>Picea</i> *	Caryophyllaceae
<i>Pinus</i> *	Chenopodiaceae*
<i>Populus</i> *	Crassulaceae
<i>Alnus</i> *	Cyperaceae
<i>Dryas</i>	Fabaceae
Ericales	Onagraceae
<i>Myrica</i> *	<i>Oxyria/Rumex</i>
<i>Salix</i>	Papaveraceae
<i>Shepherdia</i> *	<i>Plantago</i>
	Poaceae
	Polygonaceae
	Ranunculaceae
	Rosaceae
	Saxifragaceae
	Scrophulariaceae
	<i>Thalictrum</i> *
	Tubuliflorae/Liguliflorae

Taxa that do not grow on Baffin Island today are indicated by *.

of these interpolations was assessed by comparisons of observed and estimated values for each meteorological station's locality. Observed versus estimated relationships produced root-mean-squared error (RMSE) of ± 1.31 °C ($r=0.98$) for mean annual air temperature, ± 1.23 °C ($r=0.96$) for July air temperature, ± 2.19 °C ($r=0.95$) for January air temperature, and ± 119.13 mm ($r=0.93$) for annual precipitation. Thus, the modern environmental gradients embraced by the 400 modern pollen localities were -19.4 to 5.1 °C for mean annual air temperature, 3.5 to 18.2 °C for July air temperature, -36.8 to -4.1 °C for January air temperature, and 81 to 2470 mm for mean annual precipitation.

3.3.3. Correspondence analysis and canonical correspondence analysis

Correspondence and canonical correspondence analyses (CA and CCA) were used to explore the relationships between the 400 modern pollen assemblages and climatic parameters. Both techniques exploit unimodal (Gaussian) ordination, as either indirect (CA) or direct (CCA) gradient analysis (ter Braak and Prentice, 1988). Thus, while the CA is restricted to matrix of 34 taxa and 400 sites, the CCA constrained an identical matrix to linear combinations of the following variables: latitude, longitude, altitude, mean annual air temperature, July air temperature, January air temperature, and mean annual precipitation. Prior to ordination, relative frequencies of the 34 included taxa were square-root transformed, and rare taxa were not down-weighted. On the ordination plot the 400 modern sites were grouped into nine geographical regions: western Canada (WC), James Bay (JB), northern Quebec (NQ), Fort Chimo–Diana Bay (FCD), Baffin Island (B), Arctic islands (A), and Greenland (G). Following initial ordinations restricted to modern samples, fossil assemblages were entered passively, that is, projected onto the ordination space defined by the modern samples without influencing the analysis in any other way. This allowed the fossil samples to be viewed graphically alongside the most similar assemblages from the modern database. CA and CCA were implemented with CANOCO v. 4 (ter Braak and Šmilauer, 1998).

3.3.4. Best modern analogues

The best modern analogue (BMA) technique assumes that fossil samples with a pollen assemblage similar to a modern assemblage were produced by similar vegetation and, by inference, under similar climatic regimes (Overpeck et al., 1985; Guiot et al., 1989; Anderson et al., 1989; Guiot, 1990; Andreev et al., 2003, 2004b; Jackson and Williams, 2004).

Similarity between fossil and modern assemblages was assessed using the squared-chord-distance (SCD) dissimilarity metric (Overpeck et al., 1985; Gavin et al., 2003). The SCD (d^2) between fossil (t) and modern (i) pollen assemblages were calculated based on differences in the relative frequencies (p) of each taxon ($j=1$ to m ; $m=34$) as follows:

$$d_{it}^2 = \sum_j ((p_{ij})^{1/2} - (p_{tj})^{1/2})^2$$

Values of SCD can vary between 0 and 2, with larger values indicating greater dissimilarity. Overpeck et al. (1985), using 1618 sites with alternately 15 and 40 taxa, showed that an SCD below 0.12 indicates that a modern analogue exists, but that an SCD of 0.15 remains applicable in situations where poorer analogues are found. Anderson et al. (1989), using 303 modern sites and 25 taxa, proposed SCD thresholds of 0.095, 0.185 and 0.400 for 'good analogues', 'analogues', and 'possible analogues', respectively. The threshold SCD produced by 3Pbase software (Guiot and Goeury, 1996) was different because it exploited Monte Carlo simulations of the modern data, whereby modern assemblages were successively extracted at random from the population with replacement, and the best-fitting assemblage is obtained (Guiot et al., 1989; Guiot, 1990). This was repeated s times, providing s best analogues from which confidence intervals are calculated. Here, we retained the five best analogues for each fossil assemblage. The distance between pairs randomly taken in the modern database averaged 0.62, with an average deviation of 0.31. The average minus average deviation gave the adopted threshold for SCD of 0.31 for the 400 modern sites and 34 taxa. The reconstructed July air temperature for a fossil assemblage t (r_t) (Guiot et al., 1989) was indexed by the July air temperature of the 5 best modern analogues:

$$r_t = \left(\sum_i c_i / d_{it}^2 \right) / \sum_i (1 / d_{it}^2)$$

The accuracy of reconstructions was given by the SCD values of the first and the fifth analogues, which were fitted around the reconstructed July air temperature curve. If the distance of the closest analogues was higher than the threshold, no reconstruction is attempted.

The overall reliability of the BMA approach was evaluated by estimating the modern climate of the reference sites based on their own pollen assemblages. Observed versus estimated modern July air temperature produced root-mean-squared error (RMSE) of ± 1.02 °C ($r=0.97$), which was lower

than the RMSE for the climatic data themselves. This high degree of accuracy suggested that the inclusion of exotic pollen taxa in the modern pollen database was entirely justified and likely advantageous.

4. Results and interpretation

4.1. Sediment stratigraphy and chronology

The lithostratigraphy of the three cores revealed broad similarities (Figs. 2A, 3A, 4A). Although the basal minerogenic units differed slightly between lakes, from diamict in the Fog Lake core to stony lacustrine sediment in the other cores, in all cases these facies related to deglaciation of the uplands prior to the last interglacial (Steig et al., 1998). These deglacial sediments were overlain by compacted, dewatered gyttja with low magnetic susceptibility signatures. Aquatic mosses were common in this material. In the Fog and Brother-of-Fog lake cores, this lower gyttja was

capped by a stratified minerogenic unit, which in turn was overlain by Holocene gyttja. In the Amarok Lake core, Holocene gyttja unconformably overlay the older organic sediments directly. In both the Brother-of-Fog and Amarok lake cores, the lowermost Holocene gyttja was black with distinctive laminations of siderite (FeCO₃), implying a chemically-reducing sedimentary environment (Wolfe and Smith, 2004). These reduced zones were in turn overlain by faintly stratified to massive olive gyttja.

Relevant radiocarbon dating results are reported in uncalibrated ¹⁴C years BP. The finite dates from the lower gyttja reported in Table 1 must be viewed, conservatively, as minimum ages. This is because finite dates in the 37–60 ka BP range have been obtained on both Baffin Island lake sediments that are demonstrably older on the grounds of luminescence ages (Miller et al., 1999), as well as on ¹⁴C free alanine blanks (Wolfe et al., 2004). Stratigraphic and palynologic correlations strongly implied that the lower gyttja was broadly

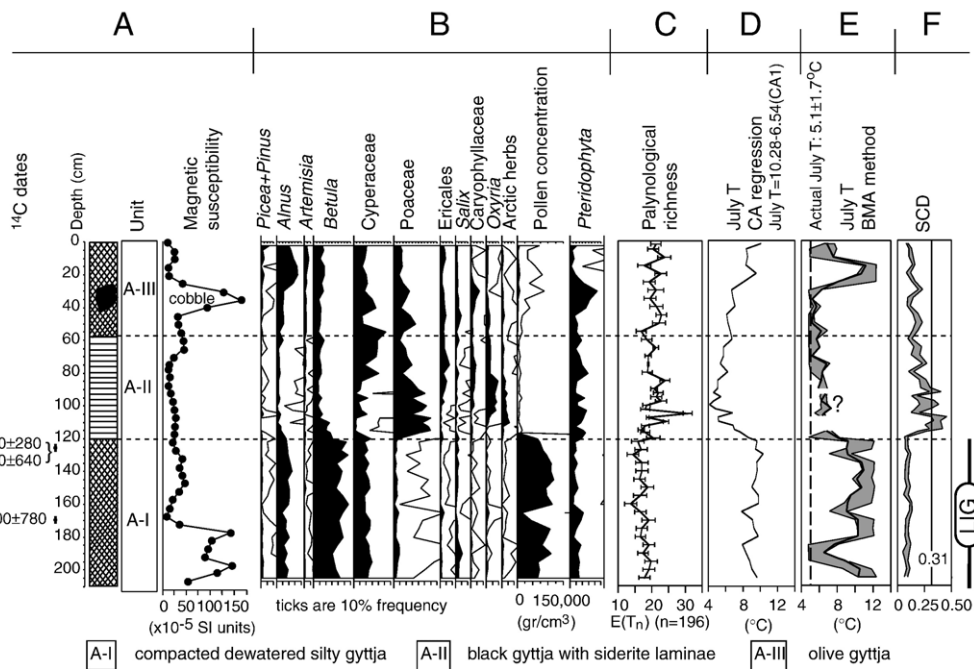


Fig. 2. Amarok Lake (66°16'N, 65°45'W, 848 m asl) summary lithology, pollen stratigraphy, and July air temperature reconstructions. A. Summarized sediment stratigraphy, magnetic susceptibility, and uncalibrated radiocarbon dates. Horizontal dashed lines delineate lithological units. B. Simplified percentage pollen diagram. Unshaded curves are 10× exaggerations of pollen relative frequencies. Taxa are ordered according to their scores on the first axis of CCA in the modern reference data set. The Arctic herbs category includes the following taxa: Ranunculaceae, Brassicaceae, Saxifragaceae, *Dryas*, Papaveraceae, Rosaceae, other Polygonaceae. C. Expected taxonomic richness (E(T_n)) as estimated by rarefaction analysis, with 95% confidence intervals shown as horizontal bars (Birks and Line, 1992). D. July air temperature reconstructions based on the CA regression (see Fig. 5C). E. July air temperature reconstructions based on closest modern analogues. The thick curve is the weighted mean July air temperature associated with the five closest analogues. The grey area represents the confidence interval. The vertical dashed line shows the actual July air temperature (Environment Canada, 2004). F. The squared-chord distance (SCD) of the first and the fifth analogue with each fossil spectrum. The vertical line shows the adopted threshold value (0.31). LIG: last interglacial interval.

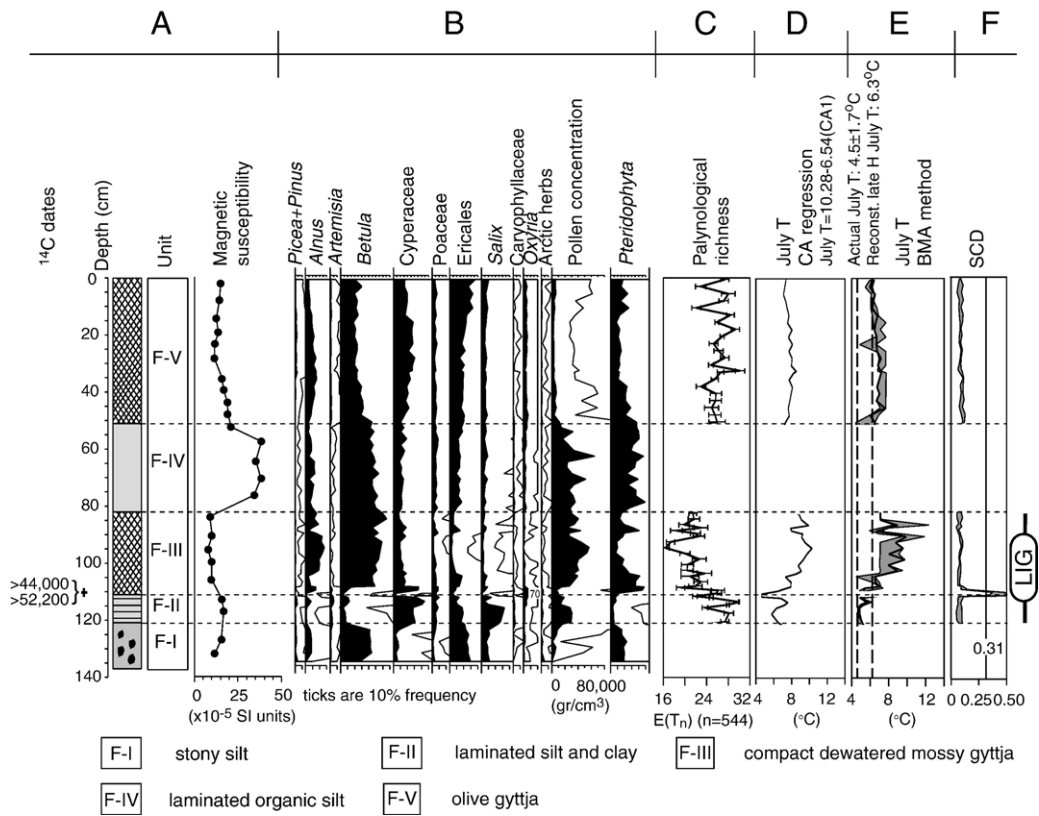


Fig. 3. Fog Lake (67°11'N, 63°15'W, 460 m asl) summary lithology, pollen stratigraphy, and July air temperature reconstructions. Legends for A–F are as for Fig. 2. Note that the *Oxyria* pollen curve is truncated at 110 and 112 cm. At these levels, *Oxyria* pollen frequency reaches 70%.

coeval in each of the lakes, so that, given the non-finite ^{14}C results from Fog Lake (Table 1), it was safely assumed that each of these units (A-I, F-III, B-III) was deposited prior to 50 ka BP.

Infrared-stimulated luminescence dates from the lower gyttja in Fog Lake (Unit F-III) produced ages of 94 ± 8 to 96 ± 8 ka BP ($n=4$), which were possibly minimum ages (Wolfe et al., 2000). Adequate zeroing of the luminescence signal was suggested by comparisons to lithologically-similar sediments of Holocene age. However, further luminescence ages from the lower gyttja in Brother-of-Fog Lake (Unit B-III) yielded maximum limiting ages of <122 and <145 ka BP, rather than clear finite ages. In contrast to Fog Lake, there was clear evidence of incomplete solar resetting in the sediments of Brother-of-Fog Lake, indicating the presence of a population of charges stored in deep, thermally-stable, electron traps that were not reset during sediment transport and deposition (S.L. Forman, personal communication, 2003).

Dating the minerogenic unit separating the two organic units in Fog and Brother-of-Fog lake cores also proved challenging because of reworked organic

matter, in particular the humic acid fraction, which produced erroneous ^{14}C ages in the 14–16 ka BP range (Wolfe et al., 2000). Subsequent dates on mosses and chironomid head capsules from these sediments provided early Holocene ages (Wolfe et al., 2004), suggesting a prolonged depositional hiatus likely representing most or all of MIS 4, 3 and 2. In Fog and Brother-of-Fog lakes, the minerogenic sediments that separated the last interglacial and Holocene organic sediments probably reflected rapid deposition associated with erosion of largely unvegetated catchments, as climate began to warm in the earliest Holocene.

Despite these various chronological complexities, what can be stated with a certain degree of confidence is that: (1) the basal organic units (A-I, F-III and B-III) were deposited within MIS 5 and appeared to be neither older than ~ 145 ka BP, nor younger than ~ 90 ka BP; (2) based on their low magnetic susceptibility, overall thickness, and low bulk density, these sediments represented intervals of deposition of comparable duration to the Holocene; (3) there were prolonged intervals of non-deposition between the formation of

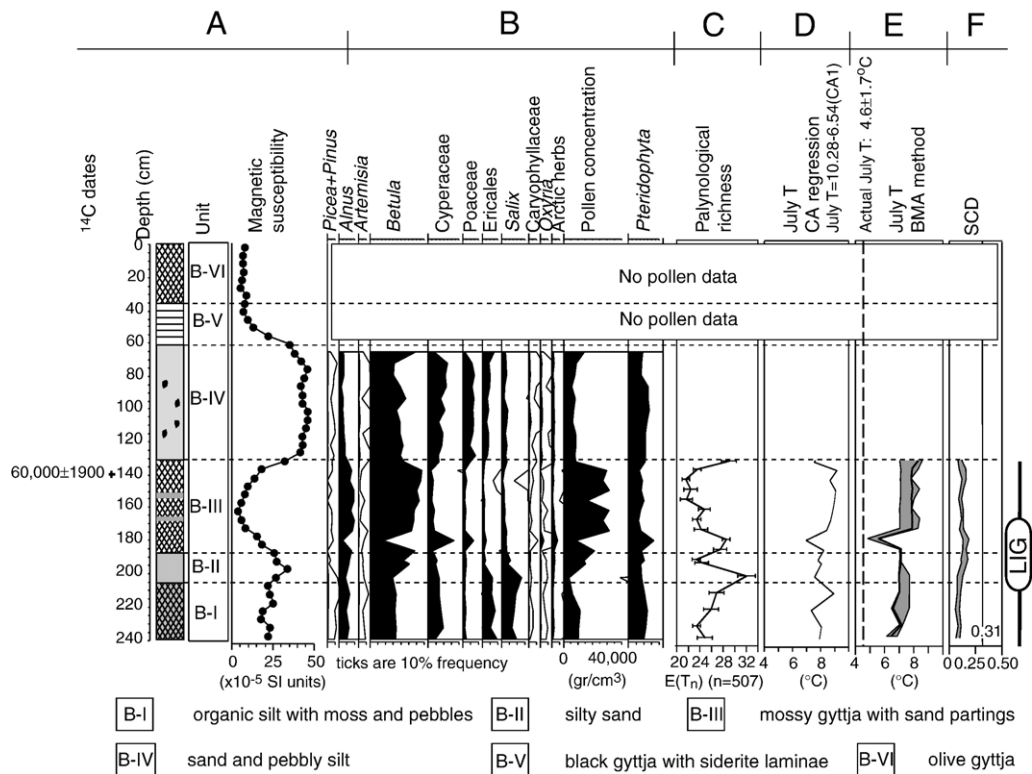


Fig. 4. Brother-of-Fog Lake (67°11'N, 63°15'W, 380 m asl) summary lithology, pollen stratigraphy, and July air temperature reconstructions. Legends for A–F are as for Figs. 2 and 3.

MIS 5 and Holocene gyttjas; and (4) the re-initiation of sedimentation in the early Holocene reworked organic matter of last interglacial age, contaminating both pollen assemblages and sediment humic acid pools. Because both pollen and chironomid assemblages in these sediments indicated summer conditions warmer than the Holocene, we tentatively ascribed them to the last interglacial *sensu stricto* (MIS 5e).

4.2. Pollen analysis of the fossil sequences

Pollen sums of at least 500 grains were attained in all samples except unit A-II, where sums ranged from 200 to 500 grains. Over 45 spermatophyte taxa were identified, as well as 11 pteridophyte and 3 algal taxa. Simplified relative frequency pollen diagrams for each of the three lakes are presented (Figs. 2B, 3B, 4B), with taxa ordered according to their CCA axis 1 scores (Birks, 1993). Because CCA axis 1 was negatively correlated with July air temperature, taxa with low (negative) scores were more characteristic of 'warm' environments (left side of diagrams), whereas those with positive scores were characteristic of 'cold' environments (right side).

4.2.1. Pollen concentrations

The last interglacial sediment in Amarok and Fog lakes yielded strikingly higher pollen concentrations than Holocene gyttja. In Amarok Lake, the mean pollen concentration in the lower gyttja (A-I) was $84,800 \pm 29,200$ grains/cm³, in comparison to 4000 ± 2700 grains/cm³ in Holocene gyttja (A-III) (Fig. 2B). In Fog lake, the mean concentration in the lower gyttja was $30,000 \pm 13,000$ grains/cm³ (F-III), and 4300 ± 1400 grains/cm³ in the Holocene (F-V) (Fig. 3B). Last interglacial gyttja of Brother-of-Fog Lake (B-III) had a mean pollen concentration of $25,000 \pm 8000$ grains/cm³ (Fig. 4B). The higher concentration of pollen in the lower gyttja was in part due to dewatering and compaction of the sediment. However, bulk densities of the last interglacial gyttja were only slightly less than Holocene sediments, and so density differences may have accounted only for a small fraction of the differences in pollen concentrations. We conclude that pollen influxes must have been significantly higher during the interglacial relative to the Holocene.

In Fog Lake, the early Holocene minerogenic unit (F-IV) that overlay last interglacial sediment also produced extremely high mean pollen concentrations ($30,300 \pm$

13,300 grains/cm³) (Fig. 3B). These were due to re-deposition of last interglacial pollen from surrounding soils, before local vegetation became sufficient to stabilize the catchment. The mean pollen concentration in the correlative minerogenic unit in Brother-of-Fog Lake was significantly lower (B-IV: 7700±1050 grains/cm³). Here too, we infer that much of this pollen was reworked from last interglacial soils at the onset of the Holocene, based on the similarity of assemblages with interglacial deposits. No paleoclimatic inferences were derived from these reworked assemblages.

4.2.2. Pollen assemblages

Last interglacial pollen assemblages of all three sequences were strongly dominated by shrubs (*Betula* and *Alnus*), with secondary contributions from arctic herb and boreal taxa (*Picea*, *Pinus* and *Artemisia*, among others) (Figs. 2B, 3B, 4B). *Betula* grains in the last interglacial gyttja (units F-III and A-I) were 2–3 times more abundant than in Holocene counterparts (units F-V and A-III). Furthermore, *Betula* grain diameters in these sediments ranged from 19 to 24 µm (mean 21 µm), confirming that they originated from shrub and not tree forms (Wolfe et al., 2000). In the Fog Lake core, *Alnus* pollen was 1.5 times more abundant in last interglacial sediments than anytime during the Holocene (Fig. 3B). However, in Amarak Lake relative frequencies of *Alnus* were similar in MIS 5 and Holocene gyttjas (Fig. 2B).

In the last interglacial sediments of Fog Lake, there was evidence for a local succession from a colonizing herb tundra to a denser shrub tundra (units F-II and F-III) (Fig. 3B). The lower unit (F-II) depicted an early postglacial vegetation dominated by herbs (e.g., *Oxyria*, Cyperaceae and *Salix herbacea*-type), and the upper unit (F-III) one dominated by *Betula* and *Alnus* with a low representation of long-distance and high arctic herb taxa. This suggested that relatively dense low arctic shrub tundra with *Betula* populations grew locally, although birch does not grow near the site today. Within this zone, two decreases in the relative frequency of *Alnus* were noted (108–104 and 89–87 cm) (Fig. 3B). These were both associated with concomitant increases in Cyperaceae, *Salix* and Ericales pollen, as well as pteridophyte spores, and were interpreted as episodes of herb tundra alternating with shrub tundra vegetation. Sediments at the base of the last interglacial gyttja from Amarak Lake showed similar subtle changes in pollen assemblages, with arctic herbs, *Salix* and boreal trees better represented here, and *Alnus* less abundant. This palynological change corresponds to elevated magnetic susceptibility, suggesting an unstable catchment (Fig. 2A, B).

The pollen content of units B-I and B-II of Brother-of-Fog Lake also reflected local vegetation changes during the last interglacial (Fig. 4B). Higher relative frequencies of Cyperaceae, Ericales and *Salix* were observed in units B-I and B-II, relative to overlying interglacial gyttja (unit B-III) (Fig. 4B), but representation of shrub taxa (*Betula*, *Alnus*) remained high by comparison to Fog Lake units F-II and F-III (Fig. 3B).

The pollen content of the minerogenic units separating last interglacial and Holocene gyttjas in Fog and Brother-of-Fog lakes (F-IV and B-IV) contained high relative frequencies of *Betula*, but lower representations of *Alnus* (Figs. 3B and 4B). In unit B-IV, Cyperaceae, Poaceae, Ericales and *Salix* were more abundant than in the last interglacial gyttja, whereas only Ericales showed higher relative frequency in Fog Lake unit F-IV. The pollen content observed in units F-IV and B-IV was an admixture of reworked MIS 5 and early Holocene pollen grains, with the early Holocene component better registered in Brother-of-Fog Lake.

In the Holocene sediments of Amarak Lake, there was evidence for a local succession from a colonizing herb tundra dominated by Poaceae, *Oxyria* and Cyperaceae (unit A-II), to a more stable herb tundra (unit A-III) (Fig. 2B). The mid-Holocene *Alnus* rise registered in Amarak and Fog lakes is a common feature in Baffin Island pollen diagrams (e.g. Short et al., 1985; Mode and Jacobs, 1987; Miller et al., 1999), associated with a higher boreal pollen taxa representation derived from long-distance transport. The pollen content of the Holocene gyttja of Fog Lake (unit F-V) is typical of a mid-Arctic herb tundra vegetation with high relative frequencies of Cyperaceae, Ericales and *Betula* (Fig. 3B). Further details of the Fog Lake pollen diagram are presented elsewhere (Wolfe et al., 2000).

4.2.3. Palynological richness

Stratigraphic profiles of rarefaction-estimated palynological richness are presented for each core on Figs. 2C 3C and 4C. In general, palynological richness was lowest in last interglacial sediments dominated by shrubs (A-I, F-III, B-III), and higher whenever shrub pollen representation decreased (F-II, B-II). These intervals of elevated richness correspond with local herb tundra expansions. Indeed, closed yet productive shrub tundra is expected to produce lower palynological richness than more open and less productive herb tundra (Moore et al., 1991). Furthermore, fewer exotic pollen grains are represented in productive shrub tundra assemblages relative to more locally impoverished herb tundra. Thus, palynological richness of Baffin

Island lake sediments appeared higher for open herb tundra than for denser shrub tundra vegetation.

4.2.4. Summary

Palynological results from the last interglacial sediments of all three investigated lakes showed the following characteristics: (1) very high pollen concentrations relative to the Holocene; (2) prolonged intervals dominated by the shrub taxa *Betula* and *Alnus* with relatively few arctic herb and long-distance pollen grains; (3) low palynological richness of these intervals as the product of dense shrub-dominated tundra vegetation; and (4) occasional intervals of herb tundra, particularly at the onset of the last interglacial.

In comparison, Holocene pollen assemblages exhibited higher richness as the product of sparser and less productive herb tundra. From these results, we conclude that shrub tundra dominated by *Betula*, perhaps including the local presence of *Alnus*, colonized Cumberland Peninsula during the last interglacial.

4.3. Climate–vegetation relationship

Correspondence analysis (CA) of the 400 modern reference sites was used to explore the main pattern of taxonomic variation across the Arctic North America (Fig. 5A, B). The first CA axis accounted for 24.1% of total variance ($\lambda_1=0.242$), whereas the second CA axis

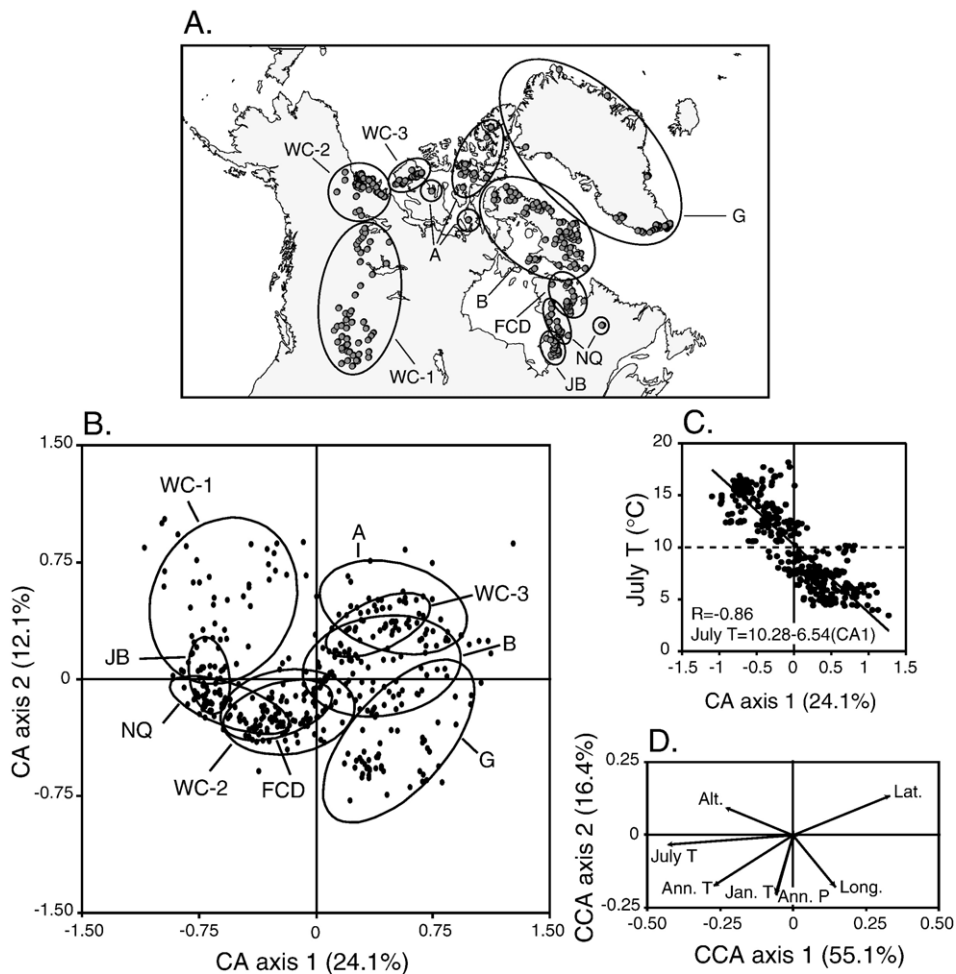


Fig. 5. A. Locations of the 400 lake sediment surface samples used to construct the modern pollen database. The 400 sites have been grouped in nine geographical regions: Western Canada (WC), James Bay (JB), northern Québec (NQ), Fort Chimo–Diana Bay (FCD), Baffin Island (B), Arctic islands (A) and Greenland (G). B. Results of correspondence analysis (CA) ordination showing sample scores from the 400 modern sites. A 95% ellipse is drawn around the reference sites of each region. C. Plot of CA axis 1 sample scores against interpolated July air temperature. The horizontal dashed line delineates sites in the Low Arctic from those occupying forest tundra. D. Canonical correspondence analysis (CCA) plot of environmental gradients associated with the 400 modern sites. Note that Jan. T and Ann. P are nearly perfectly superimposed.

represented 12.1% ($\lambda_2=0.122$). The third CA axis accounted for 8.4% ($\lambda_3=0.084$) and was not considered further. A biplot of CA sample scores in the low-dimensional space defined by axes 1 and 2 confirmed that a strong spatial (latitudinal) structure was preserved by the modern pollen assemblages (Fig. 5B). Sites from Low, Mid, and High Arctic phytogeographical zones produced positive scores on CA axis 1, whereas sites from forest tundra and boreal forest resulted in negative scores. Furthermore, among the tundra sites, CA axis 2 faithfully differentiated herb tundra vegetation (positive scores) from shrub tundra (negative scores).

Because the CA revealed a clear latitudinal pattern, axis 1 had a significant negative correlation ($r=-0.86$) with July air temperature (Fig. 5C). Furthermore, the CA allowed clear differentiation between Low Arctic and forest tundra (boreal forest) vegetation as represented by their corresponding pollen assemblages, indicating that this transition occurred at a July air temperature of $\sim 10^\circ\text{C}$ (Fig. 5C). It is independently established that the boreal forest–tundra ecotone (or treeline), which reflects the average position of the Arctic Front, coincides with the 10°C mean July air temperature isotherm (e.g., Bonan et al., 1992; Foley et al., 1994; Pielke and Vidale, 1995).

A canonical correspondence analysis (CCA) constraining the 34 pollen taxa to 7 environmental variables (Fig. 5D) was also conducted. The first two CCA axes

explained 26.8% of the variance in the pollen assemblage data ($\lambda_1=0.208$; $\lambda_2=0.062$; total inertia: 1.006), with pollen–environment correlations of 0.933 for axis 1 and 0.758 for axis 2. This corresponded to 71.5% of the total pollen–environment relationship being explained (55.1% and 16.4% for axis 1 and 2, respectively). Monte Carlo permutation tests indicated that the canonical correlation between the pollen and environmental matrices was highly significant ($p=0.001$ after 999 permutations). As suspected from the CA results, axis 1 in CCA was strongly correlated with July air temperature, whereas axis 2 was negatively correlated with both annual precipitation ($r=-0.61$) and January air temperature ($r=-0.60$) (Fig. 5D). For the 400 lakes above 50°N latitude in northwestern Canada, northern Québec, the Canadian Arctic Archipelago, and Greenland, the weighted correlation between annual precipitation and January air temperatures was 0.76, and that between annual precipitation and July air temperatures was 0.16.

4.4. Paleoclimate reconstructions from pollen assemblages

4.4.1. Inferences from correspondence analysis

Fossil assemblages were passively entered in the CA of the 400-lake modern assemblages (Fig. 6A and B). All samples from Fog, Brother-of-Fog, and Amarak

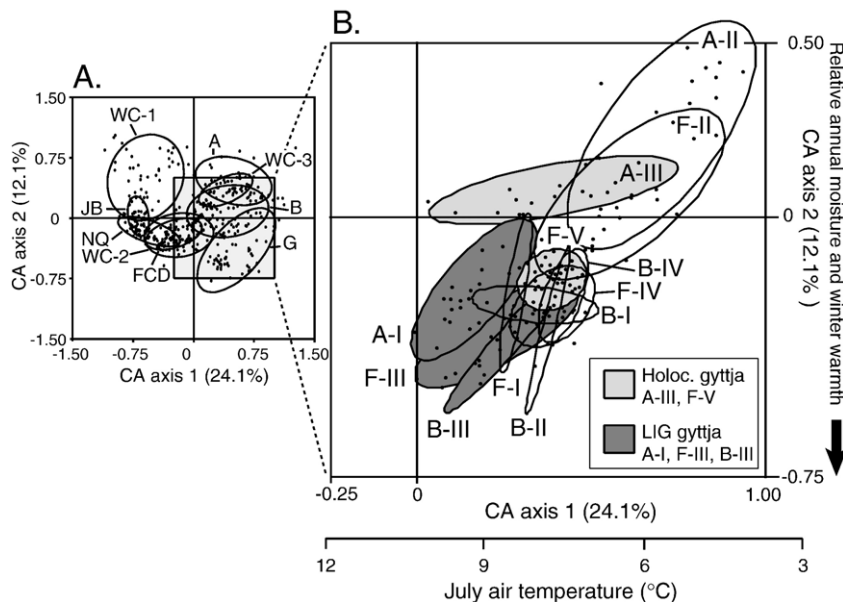


Fig. 6. A. Correspondence analysis (CA) ordination diagram of sample scores from the 400 modern assemblages. A 95% ellipse is drawn around the reference sites of each region. B. Projection of fossil assemblages from Amarak, Fog, and Brother-of-Fog lakes in the ordination spaces defined by the 400 modern assemblages. A 95% ellipse is drawn around the fossil assemblages of each unit. The July air temperature scale has been calculated with the CA regression: July air $T=10.28-6.54$ (CA axis 1 sample score) (see Fig. 5C).

lakes produced positive CA axis 1 scores. Last interglacial samples (units A-I, F-III, B-III) had more negative scores than those representing the Holocene (units F-V, A-III), suggesting consistently higher July air temperatures (see Fig. 5C, D). The last interglacial samples also had negative scores on axis 2 (units A-I, F-III, B-III) (Fig. 6B), implying moister precipitation regimes.

The palynological similarity of last interglacial samples from all three lakes (units A-I, F-III and B-III) suggested that they collectively reflected the widespread development of shrub tundra vegetation with local *Betula* populations on Cumberland Peninsula. In comparison, the pollen content of Holocene gyttja from Amarok and Fog lakes was considerably more site specific (units A-III and F-V). This type of specificity appeared more characteristic of herb tundra vegetation.

The linear correlation between CA axis 1 modern sample scores and July air temperature (Fig. 5C) was given by equation: July T (°C) = 10.28 – 6.54 (CA axis 1 sample score). Applying this relationship to the fossil samples entered passively in the ordination enabled a first-order appreciation of the July air temperatures associated with interglacial pollen assemblages. The quantitative reconstruction of July air temperature based on this method suggested that last interglacial July air temperatures were 4 to 6 °C warmer than present at all three lakes, that is, between 7.5 and 10 °C (Figs. 2D, 3D, 4D).

4.4.2. Quantitative July air temperatures from best modern analogues

Pollen-based reconstructions of July air temperature using the best modern analogue method are also presented in Figs. 2E, 3E, 4E. The modern database contained close analogues for both Holocene and last interglacial assemblages, with SCD for the 5 best analogues well within threshold values adopted by 3Pbase software (0.31) and proposed by Overpeck et al. (1985) (0.15) (Figs. 2F, 3F, 4F). However, reconstructions of modern July air temperatures from core tops from Amarok and Fog lakes resulted in overestimates (by 1.5 °C; Figs. 2E, 3E). These discrepancies were of the same order as inferred July air temperature RMSE (± 1.02 °C), and were within the standard deviation of measured July air temperatures for Cumberland Peninsula (4.6 ± 1.7 °C for 1971–2000; Environment Canada, 2004). For the last interglacial sediments, July air temperatures reconstructed by best modern analogues were 4 to 5 °C warmer than present for Amarok and Fog lakes, producing values ranging from 8 to 10 °C (Figs. 2E

and 3E). Results from Brother-of-Fog Lake were slightly cooler (between 7 and 8 °C) (Fig. 4E).

However, the very beginning of the last interglacial at Fog Lake (unit F-II), where herb pollen taxa was dominant, was ~ 1.5 °C colder than late Holocene reconstructions. Furthermore, the two subsequent episodes of herb tundra reappearance within the last interglacial at Fog Lake (unit F-III) also produced July air temperatures comparable to the late Holocene. Pollen from units B-I and B-II in Brother-of-Fog Lake, which combined abundant herb pollen while maintaining strong representations of *Betula* and *Alnus*, produced July air temperatures 1 °C warmer than the episodic herb tundra phases noted in Fog Lake, and may have represented July air temperatures comparable to, or slightly warmer, than those of the late Holocene. The lower portion of the last interglacial in Amarok Lake, with abundant *Salix*, arctic herbs, and boreal tree pollen (but fewer *Betula*), contained an interval of cool reconstructed July air temperatures (Fig. 2B, E).

4.4.3. Summary

Last interglacial pollen assemblages from the three investigated sites on Baffin Island were most comparable to modern assemblages from southwestern Greenland between 60–64°N and 44–40°W. In this region, green alder (*A. crispa*), shrub birch (*B. nana*, *B. glandulosa*) and dwarf tree birch (*B. pubescens*) grow locally (Fredskild and Ødum, 1990; Fredskild, 1996). July air temperature is currently 7.4 ± 1.8 °C (Cappelen et al., 2001).

Table 3

Summary of pollen-based July air temperature reconstructions (in °C) from the three studied lakes

Site	Method ^a	LIG ^b	Max LIG	Early Holocene ^c	Late Holocene ^d
Amarok	CA	9.5±0.4	10.3	6.4±1.3	9.0±0.9
Amarok	BMA	9.9±0.8	11.0	6.6±1.8	7.1±0.4
Amarok	Consensus	9.7±0.7	n.a.	6.5±1.5	8.1±1.2
Fog	CA	9.0±0.8	10.3	7.8±0.4	7.6±0.3
Fog	BMA	8.2±1.2	10.0	6.7±0.4	6.5±0.3
Fog	Consensus	8.6±1.1	n.a.	7.2±0.6	7.0±0.6
Brother-of-Fog	CA	8.8±0.3	9.2	n.a.	n.a.
Brother-of-Fog	BMA	7.8±0.3	7.9	n.a.	n.a.
Brother-of-Fog	Consensus	8.3±0.6	n.a.	n.a.	n.a.

^a CA: correspondence analysis regression, BMA: best modern analogue, Consensus: CA and BMA averaged.

^b Last interglacial.

^c >5 cal ka BP.

^d <5 cal ka BP.

From both methods of quantitative reconstruction applied here, July air temperatures of the last interglacial on eastern Baffin Island attained between 8 and 10 °C (Table 3), significantly warmer than present. For example, the current mean July air temperature for Cumberland Peninsula is 4.6 ± 1.7 °C (Environment Canada, 2004). At the optimum of the last interglacial, summer temperatures were high enough to allow the establishment of dense shrub tundra vegetation, comparable to that of modern southwestern Greenland, as far north as Cumberland Peninsula on Baffin Island. This implies a 300–500 km northward migration of the Low Arctic phytogeographical zone. We do not question the presence of shrub *Betula* in the immediate vicinities of the lakes studied here during the last interglacial, in part because local populations occur within 100 km. Although our reconstructed summer temperatures could have allowed for the presence of *Alnus* locally, we remain unable to confirm the latter's presence in absolute terms on Cumberland Peninsula in the last interglacial.

5. Conclusion

Pollen analysis of three lacustrine sediment sequences from Cumberland Peninsula provided a basis for comparing interglacial vegetation and climate of east-central Baffin Island with that of the Holocene. The vegetation of the last interglacial period on east-central Baffin Island was primarily Low-Arctic in character. Shrub birch-dominated tundra expanded considerably, driven by summer temperatures significantly warmer than present. The northward expansion of birch may also have been favoured by deeper snow cover associated with warmer winters and enhanced precipitation (see Fig. 6B).

The exact paleoenvironmental and paleoclimatic dynamics throughout the last interglacial on Cumberland Peninsula remain partially compromised by the problems presented by lake sediment chronology. Nonetheless, our data suggested strong regional coherence within the palynological signature of the last interglacial, more than during the Holocene, in which vegetational histories were more site-specific. Based on the clear evidence of terrestrial summer warmth greater than at any time in the Holocene, we equate the interglacial sediment with the last interglacial *sensu stricto*, ca. 117 to 130 ka BP (MIS 5e).

Results that emerge from the application of the correspondence analysis and best modern analogue techniques indicated that July air temperatures of the last interglacial were warmer by as much as 4 to 5 °C on eastern Baffin Island (Table 3). Our quantitative July air

temperature reconstructions are thus directly comparable to both earlier qualitative estimates (LIGA Members, 1991; Bennike and Böcher, 1994), as well as more recent quantifications from ice core (NGRIP Members, 2004) and pollen (Andreev et al., 2004a) analyses. Because the warmest millennia of the last 200 ka appear to have occurred at this time, the associated biotic communities foreshadow possible future community shifts that may be associated with anthropogenic warming.

Acknowledgments

We thank Joël Guiot (CEREGE-France) and Maryse Henry (GEOTOP) for their help with the data analysis, Nicole Morasse (Université de Montréal) for her help with pollen analysis, Bent Fredskild (University of Copenhagen) and Michael Kerwin (University of Denver) for providing modern pollen data, three anonymous reviewers for their critical comments on the manuscript, and Rachel Jones for improving the English. This study was supported by the Natural Science and Engineering Council of Canada (NSERC), the Fonds québécois de la Recherche sur la Nature et les Technologies, the Climate Foundation for Climate and Atmosphere Sciences (project no GR-240), and NSF-PALE/PARCS programs (USA). Steven Forman (University of Illinois, Chicago) provided luminescence dates. Access to field sites was granted by the Inuit of Pangnirtung and Qikiqtarjuaq (formerly Broughton Island), who also provide logistical assistance and welcome advice. The Nunavut Research Institute (Nunavummi Qaujisaqtulirijikkut) provided logistical support in Iqaluit.

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