Chironomids record terrestrial temperature changes throughout Arctic interglacials of the past 200,000 yr

Yarrow Axford[1,2,†], Jason P. Briner[3], Donna R. Francis[4], Gifford H. Miller[2,5], Ian R. Walker[6], and Alexander P. Wolfe[7]

[1]*Department of Earth and Planetary Sciences, Northwestern University, 1850 Campus Drive, Evanston, Illinois 60208, USA*
[2]*Institute of Arctic and Alpine Research, University of Colorado, UCB 450, Boulder, Colorado 80309, USA*
[3]*Department of Geology, University at Buffalo, 411 Cooke Hall, Buffalo, New York 14260, USA*
[4]*Department of Geosciences, University of Massachusetts, 233 Morrill Science Center, Amherst, Massachusetts 01003, USA*
[5]*Department of Geological Sciences, University of Colorado, UCB 399, Boulder, Colorado 80309, USA*
[6]*Palaeoecology Laboratory, University of British Columbia–Okanagan, Kelowna, BC V1V1V7, Canada*
[7]*Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB T6G 2E3, Canada*

ABSTRACT

Quaternary interglacial periods provide glimpses of a warmer Arctic and useful perspectives on possible future conditions, but records of Arctic terrestrial conditions over multiple interglacial periods are rare. Here, we take advantage of a site in the Canadian Arctic where lacustrine sediments representing the past three interglacial periods are preserved in an extant lake. We use subfossil insects (chironomids) preserved in this exceptional sedimentary archive to derive temperature reconstructions through the Holocene up to A.D. 2005, through the Last Interglacial sensu stricto (marine isotope stage or MIS 5e), and a portion of the penultimate interglacial (MIS 7). Chironomid-inferred temperatures are warmest for the early Holocene and MIS 5e, two periods with enhanced Northern Hemisphere insolation forcing relative to today. Twentieth-century warming at this site apparently caused the recent extirpation of cold stenothermous chironomid taxa. Assemblages from MIS 5e have close analogs in modern training set data as determined by squared-chord distance, and MIS 5e species assemblages are very similar to Holocene assemblages at this site. MIS 7 sediments record summer temperatures similar to those of the mid- to late Holocene, followed by a descent into glacial conditions. Even MIS 7 chironomid assemblages, dating back ~200,000 yr, have close modern analogs. These lake sediments also provide direct evidence for a period of regional deglaciation between MIS 5e and the Holocene (most likely MIS 5a). To our knowledge, the data presented here represent the longest paleotemperature record thus far generated using chironomids. The existence of close modern analogs for ancient chironomid assemblages at Lake CF8 suggests that this method can provide useful paleotemperature estimates extending back hundreds of millennia.

INTRODUCTION

Biological remains preserved in terrestrial and marine sediments have made major contributions to our understanding of the Quaternary climate history of the Arctic. For example, the majority of existing proxy-based estimates of Arctic temperatures during the last interglacial period (Last Interglacial sensu stricto, i.e., marine isotope stage [MIS] 5e, ca. 130–115 ka; ka = thousands of yr B.P.; Fig. 1) are derived from biological assemblages, including vegetation, insects, marine mollusks, and foraminifera (CAPE Last Interglacial Project Members, 2006). Unfortunately, there are relatively few records from the Arctic that quantify temperature changes throughout MIS 5e (Berger and Anderson, 2000; Johnsen et al., 2001; NGRIP Project Members, 2004; CAPE Last Interglacial Project Members, 2006), and archives recording changing terrestrial conditions throughout earlier interglacial periods in the Arctic are extremely rare (Lozhkin et al., 2007; Brigham-Grette et al., 2007; de Vernal and Hillaire-Marcel, 2008; Brigham-Grette, 2009). Ice cores from Greenland provide invaluable continuous records of past climate and atmospheric composition, but the longest continuous ice-core records from the Northern Hemisphere extend only partway through MIS 5e (Johnsen et al., 2001; NGRIP Project Members, 2004).

Recent work has demonstrated that lake sediment sequences representing multiple interglacials have been preserved on Baffin Island despite repeated overriding advances of the Laurentide Ice Sheet (Briner et al., 2007), presenting a new opportunity for long-term terrestrial environmental reconstruction from a glaciated part of the Arctic. This discovery has allowed for the recovery of pre–Last Glacial Maximum (pre–MIS 2) sediments and corresponding paleoecological records from several extant Baffin Island lakes (Miller et al., 1999; Wolfe et al., 2000, 2004). The longest of these archives comes from Lake CF8, which contains sediments recording interglacial periods of at least the past 200,000 yr (Briner et al., 2007). A brief overview of major conclusions from the multiproxy 200,000 yr record has been presented previously (Axford et al., 2009a). Here, we present details of the 200,000 yr subfossil chironomid (nonbiting midge; Insecta: Diptera: Chironomidae) record and chironomid-inferred paleotemperature reconstructions from Lake CF8.

STUDY SITE

Lake CF8 (z_{max} = 10 m; surface area = 0.3 km^2; elevation = 195 m asl; 70°33.42′N, 68°57.12′W)

†E-mail: axford@northwestern.edu

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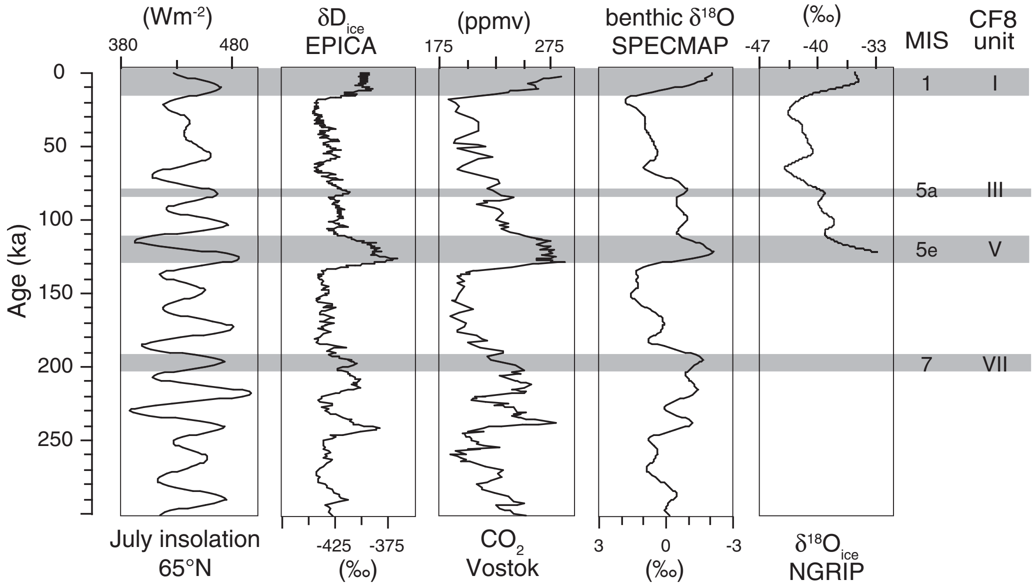

Figure 1. Quaternary context of Lake CF8 stratigraphy, compared with climate indicators for the past 450 ka: July insolation at 65°N (in Wm^{-2}; Berger and Loutre, 1991); δD of ice from Dome C, Antarctica (‰; EPICA Community Members, 2004); atmospheric CO_2 concentration over Vostok, Antarctica (ppmv; Petit et al., 1999); SPECMAP benthic foraminifera δ^{18}O stack (‰; Imbrie et al., 1984, 1989); smoothed δ^{18}O of ice from NorthGRIP, Greenland (‰; NGRIP Project Members, 2004), marine oxygen isotope stage (MIS) designations, and roman numeral designations assigned to Lake CF8 organic sediment units (Briner et al., 2007; estimated ages of organic sediment units are shown as gray bands).

sits on the low-relief Clyde Foreland on northeastern Baffin Island (Fig. 2) in Nunavut, Arctic Canada. Lake CF8 is a small through-flowing lake fed primarily by summer snowmelt. There are no extant glaciers in the lake catchment. At the nearby village of Clyde River, modern mean annual temperature (for the period A.D. 1961–1990) is −12.8 °C, and mean July temperature is +4.4 °C (Environment Canada, http://www.climate.weatheroffice.gc.ca). Clyde River's climate is mid-Arctic. Prostrate dwarf-shrub tundra vegetation surrounds the lake, which is generally ice covered for at least 9 mo each year (October–June). The local bedrock is Precambrian granite and gneiss.

Lake CF8 was overridden during the last glacial cycle by the Laurentide Ice Sheet, but previous work has demonstrated that this overriding ice was cold-based (i.e., frozen-bedded) and nonerosive (Briner et al., 2005, 2006a). In locations covered by cold-based ice during the last glaciation (Kleman and Hättestrand, 1999), little to no subglacial erosion took place, leading to the preservation of delicate features like fragile tors (Briner et al., 2003; Marquette et al., 2004), perched boulders (Stroeven et al., 2002; Briner et al., 2005), and unconsolidated depositional landforms like beach ridges and deltas (Davis et al., 2006). Ice-marginal meltwater channels and scattered erratic boulders provide the only evidence of late Pleistocene ice-sheet advances around Lake CF8 (Fig. 2; Briner et al., 2003, 2006a). The recovery of intact stratified lacustrine sediments predating the Last Glacial Maximum from Lake CF8 has provided supporting evidence for the nonerosive nature of overriding late Pleistocene ice (Briner et al., 2007), as well as a new opportunity to reconstruct Arctic paleoenvironments predating the Last Glacial Maximum.

Although pre-Holocene lake sediment records from the Canadian Arctic are rare, several such occurrences are known; their greatest density occurs along the east coast of Baffin Island (Wolfe and Smith, 2004). Last Interglacial sediments from Fog and Brother of Fog Lakes on east-central Baffin Island (Fig. 2) have been analyzed for pollen (Fréchette et al., 2006, 2008), diatoms (Wolfe et al., 2000), and chironomids (Francis et al., 2006). These lakes have yielded superposed sequences of Last Interglacial and Holocene age only; thus far, only Lake CF8 has yielded even older integlacial sediments.

MATERIALS AND METHODS

Core Stratigraphy and Geochronology

Briner et al. (2007) described the genesis, stratigraphy, and geochronology of Lake CF8 sediments in detail, so only a general summary is provided here. Cores contain multiple stratified organic lake mud units (gyttja) alternating with inorganic sand (Fig. 3) and penetrate to a total depth of 3.3 m below the sediment-water interface. Depth of penetration was limited by the stiffness of the oldest sediments, which are very dense (1.9 g cm^{-3}), compact dewatered organic sediments. Preliminary geophysical surveys using ground-penetrating radar suggest that there are older sediments yet to be recovered (G.S. Baker 2005, personal commun.), but these have thus far eluded our coring technology.

Briner et al. (2007) assigned Roman numeral designations I–VII to each of the major lithostratigraphic units in the Lake CF8 stratigraphy; we use the same designations here. Units I, III, V, and VII are gyttja; units II, IV, and VI are crudely stratified sands. Gyttja units are brown to gray-brown in color, weakly stratified to laminated, and contain varying concentrations of macrofossils (dominantly aquatic bryophytes). Sand units contain a range of grain sizes from fine to medium sand with occasional coarse sand lenses, granules, and pebbles, and they contain both lithic grains and a variety of minerals, including quartz, micas, and mafic minerals, but no detectable organic material. As described by Briner et al. (2007), gyttja units are

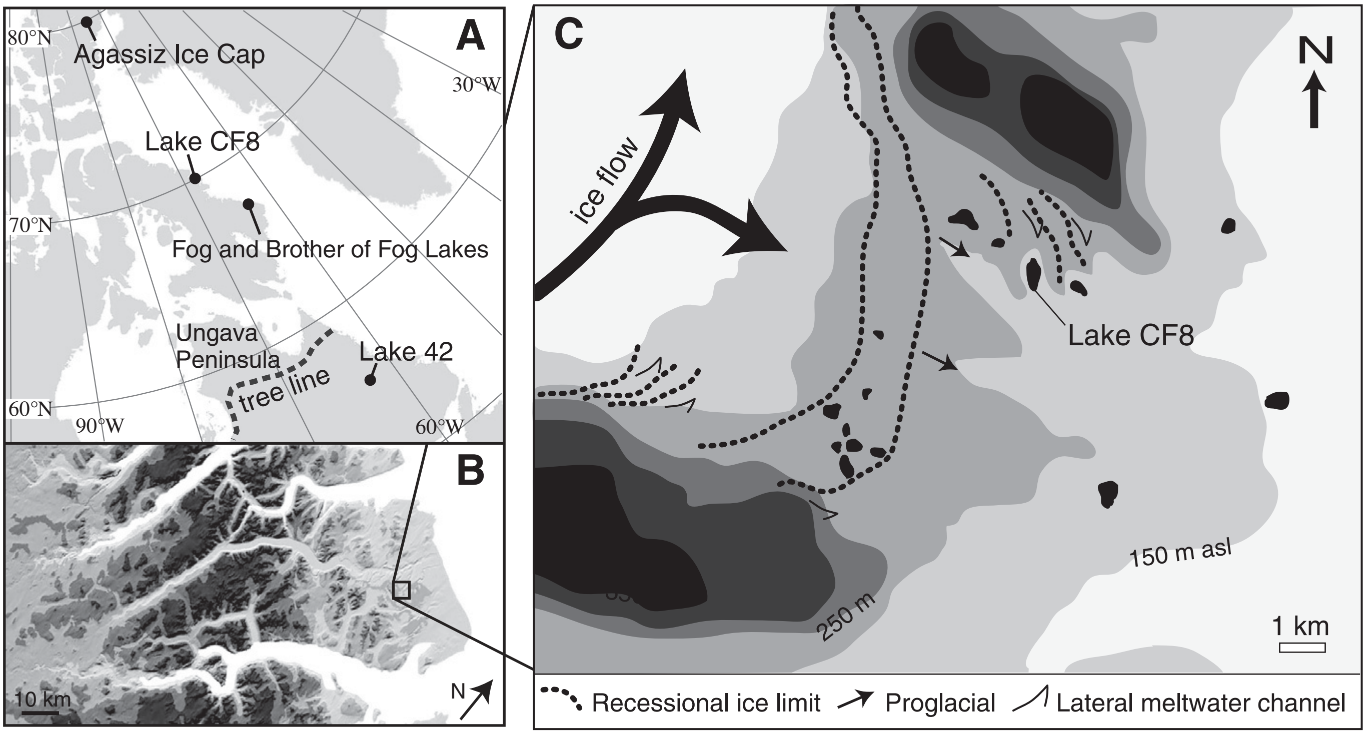

Figure 2. Location maps showing (A) regional setting of Lake CF8 and other sites mentioned in the text (dashed line is tree line), (B) position of Lake CF8 on the low-elevation interfjord Clyde foreland, and (C) glacial-geologic features surrounding Lake CF8. Topography is shown in grayscale, and lakes are shown in black. Large arrows in panel C indicate former flow directions of the Laurentide Ice Sheet within the study area.

presumed to record lacustrine deposition during interglacial or interstadial conditions; intervening periods of ice-sheet cover were characterized by nondeposition (i.e., hiatuses in the sediment stratigraphy), followed by the deposition of sand units in the lake during deglaciation. For the paleoecological study described here, we used portions of several different cores (Fig. 3) in order to work with the best preserved, most representative example of each gyttja unit. Sediment depths given herein are relative to the top of each individual core; therefore, in most cases, zero depth does not represent the sediment-water interface.

Radiocarbon ages from the upper organic unit (Unit I) span the entire Holocene (Axford et al., 2009b), and a ^{210}Pb chronology has been established for the uppermost sediments (Thomas et al., 2008). Ages have been assigned to the older stratigraphic units based upon radiocarbon and optically stimulated luminescence (OSL) dating of the organic lake-sediment units: Three different aquatic moss macrofossils from unit III all yielded nonfinite radiocarbon ages, indicating this unit is older than ca. 48 ka. Based upon the radiocarbon and OSL results, Briner et al. (2007) assigned unit V to the Last Interglacial (MIS 5e) and unit VII to a portion of MIS 7, the prior interglacial period (Fig. 1). Organic unit III is assigned tentatively to MIS 5a, based upon its position above MIS 5e and below the Holocene sediments. Sand units are assumed to record clastic sediment transport to the lake via meltwater channels during deglaciation, and unconformities are assumed to be present below each sand layer (due to hiatus in deposition during glacial periods; Briner et al., 2007).

Composition of Bulk Sediments

Qualitative proxies, including magnetic susceptibility, loss-on-ignition, and biogenic silica concentrations, were measured on bulk sediments to provide supplementary information about changing sediment composition and paleoenvironments. Percent loss-on-ignition (%LOI), which is highly correlated with the total carbon content (%C) of sediments in Clyde Foreland lakes (Briner et al., 2006b), was measured at 550 °C (Heiri et al., 2001) and is reported as wt% C of dry sediment. Biogenic silica ($BiSiO_2$) analysis followed Mortlock and Froelich (1989), except for the use of 10% Na_2CO_3 solution for $BiSiO_2$ extraction. $BiSiO_2$ concentration was measured by spectrophotometry and converted to wt% SiO_2 of dry sediments.

Chironomid Analysis

Chironomids are a diverse and nearly ubiquitous family of holometabolous two-winged flies. The chitinous head capsules of lake-dwelling chironomid larvae are often abundant and well-preserved in lake sediments, and distinctive morphology makes many subfossil head capsules recognizable to at least the generic level (Walker, 2001; Fig. 4). Many chironomid taxa have temperature-dependent species distributions (e.g., Walker et al., 1991a; Lotter et al., 1997), reflecting the effects of air and water temperatures on all stages of their life cycles (Oliver, 1971). Accordingly, the past decade has seen numerous efforts to develop quantitative models (transfer functions) for reconstructing late Quaternary paleoclimatic or paleoenvironmental variables based upon the modern distribution of chironomid species along climatic (e.g., Walker et al., 1997; Lotter et al., 1999; Brooks and Birks, 2001; Larocque et al., 2001; Barley et al., 2006) and other environmental gradients, such as lake depth, oxygen, and nutrient status (e.g., Quinlan et al., 1998; Korhola et al., 2000; Brooks et al., 2001; Brodersen and Quinlan, 2006; Langdon et al., 2006).

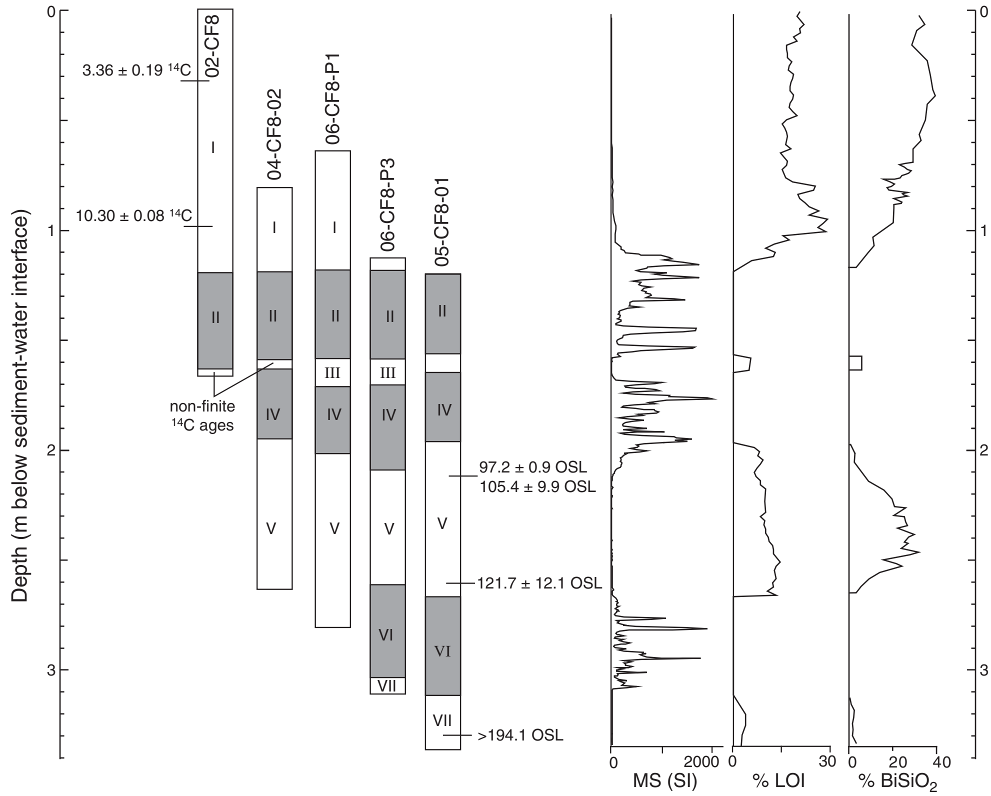

Figure 3. Summary stratigraphy and geochronology of Lake CF8 sediment cores. Depth scale indicates approximate depth below the sediment-water interface. Cores collected after 2002 intentionally bypassed some or all of the uppermost lithostratigraphic unit. Organic gyttja units are shown in white, and sand units in gray. Roman numerals for lithostratigraphic units were first designated by Briner et al. (2007). Pre-Holocene optically stimulated luminescence (OSL) ages from Briner et al. (2007) are shown in ka (thousands of yr B.P.). Representative Holocene ^{14}C ages are reported from Axford et al. (2009b) in calibrated ka. Magnetic susceptibility (MS), percent loss on ignition (LOI), and percent biogenic silica ($BiSiO_2$) data from bulk sediments are also shown.

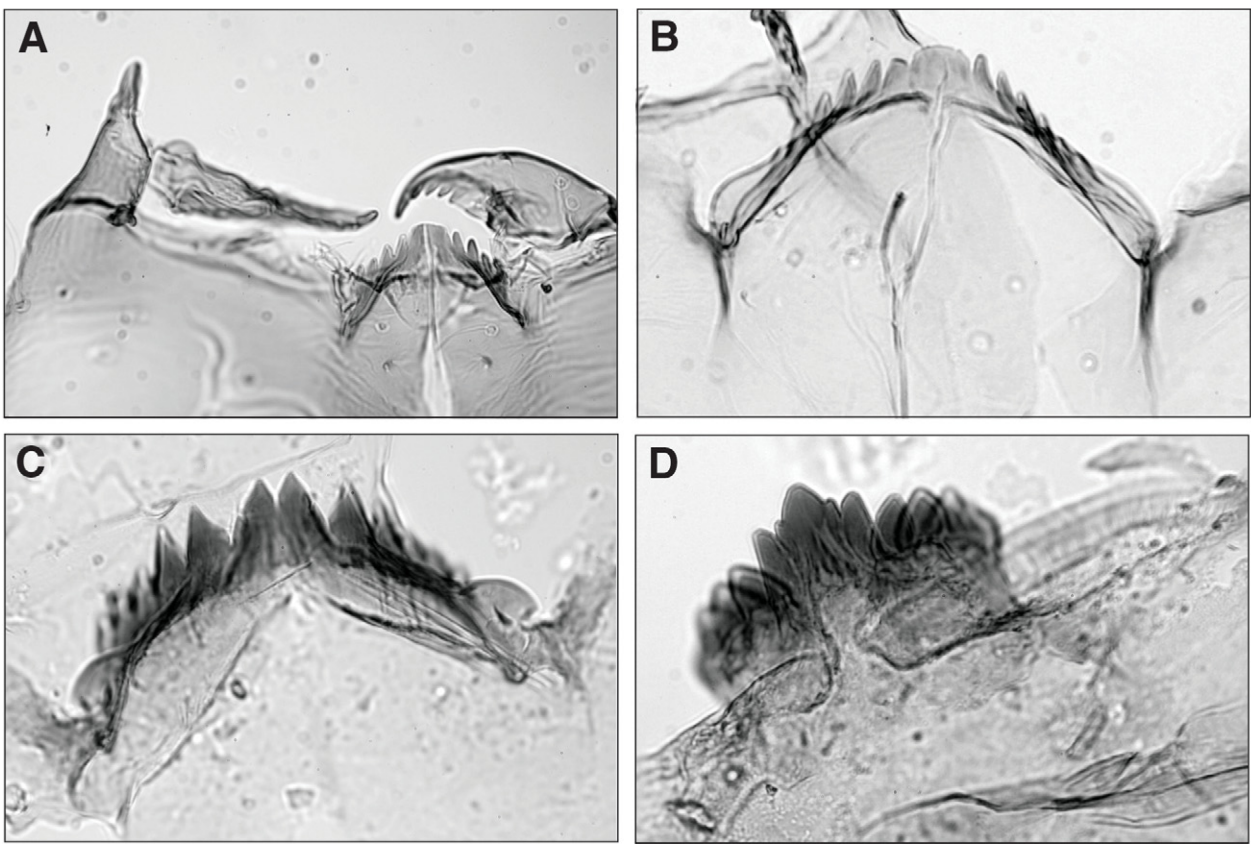

Figure 4. Photomicrographs showing preservation and morphology of representative chironomid head capsules from Lake CF8: (A) *Abiskomyia*, late Holocene (unit I; approximate width of field-of-view [FOV]—400μm); (B) *Oliveridia/Hydrobaenus*, late Holocene (unit I; FOV—150μm); (C) *Heterotrissocladius*, Last Interglacial (unit V; FOV—150μm); and (D) *Tanytarsus lugens/Corynocera oliveri* type, Last Interglacial (unit V; FOV—200μm).

Subfossil chironomid assemblages have been widely used to infer late-glacial and Holocene paleotemperatures (i.e., temperatures of the past ~14 k.y.; e.g., Walker et al., 1991b; Brooks and Birks, 2000; Cwynar and Spear, 2001; Heiri et al., 2003; Porinchu et al., 2003; Caseldine et al., 2006; Axford et al., 2007). In a few cases, the method has also been applied to older Pleistocene sediments (e.g., Hofmann, 1990, 1991; Francis et al., 2006). Subfossil chironomid remains preserved in older sediments have yielded qualitative information about Pliocene and Pleistocene paleoenvironments at several sites on Greenland (Bocher, 1995; Bennike et al., 2000; Brodersen and Bennike, 2003).

Chironomid Extraction and Identification

Chironomid analyses for this study followed published methods (e.g., Walker, 2001). Wet sediment samples for chironomid analyses were deflocculated in warm 5% KOH for 20 min and rinsed in deionized water on a 100 µm sieve. Head capsules, which were abundant and well preserved in all four gyttja units, were manually picked from a Bogorov sorting tray under a 40× power dissecting microscope and then permanently mounted on slides using Euparal. With four exceptions (described in the following), samples had minimum count sums of 50 whole-head capsules. Identifications were informed by standard reference materials (e.g., Oliver and Roussel, 1983; Wiederholm, 1983; Brooks et al., 2007). Taxonomic designations were harmonized with those of Francis et al. (2006) to allow comparison with the published calibration data, i.e., training set (see following). Taxa were subdivided further where possible (e.g., *Micropsectra*, *Paratanytarsus*, and *Tanytarsus lugens/Corynocera oliveri* type were subdivided from the subtribe Tanytarsina) but were lumped into the taxonomic designations of Francis et al. (2006) for the statistical analyses described here.

Paleotemperature Inferences and Assessment of Modern Analogs

Our ecological knowledge of the Baffin Island chironomid fauna is based upon a training set derived from subfossil chironomid assemblages from surface sediments spanning northeastern North America (Canadian Maritime provinces, Labrador, Baffin, and Devon Islands). The data set, composed of chironomid assemblages alongside an array of environmental data for each site, was first developed by Walker et al. (1991a) and later expanded by Walker et al. (1997). Francis et al. (2006) added 29 additional calibration sites on Baffin Island, refining the calibration for Arctic sites. The training set now includes 68 calibration sites and 44 chironomid taxa (Francis et al., 2006). Mean July air temperatures at the calibration sites range from 5.0 to 19.0 °C. Both July air temperature and summer water temperature are dominant environmental gradients correlating with chironomid assemblages in the training set.

Paleotemperatures were modeled using weighted-averaging regression with inverse deshrinking, following the methods of Francis et al. (2006), who found that weighted averaging models with inverse deshrinking had the greatest power (highest jackknife cross-validated r^2, or r^2_{jack}, and lowest root mean squared error of prediction, or RMSEP) in predicting temperatures from eastern Canadian chironomid assemblages. Species data were square-root transformed to counteract the dominance of very abundant species, and temperatures were modeled using leave-one-out cross-validation and the computer program C2 version 1.4.3 (Juggins, 2003). Two versions of the weighted averaging model—one employing tolerance downweighting (WA_{tol}) and one without tolerance downweighting (WA) but otherwise identical—were compared in order to assess the influence of tolerance downweighting on both air and water temperature inferences. Weighted averaging with tolerance downweighting (WA_{tol}) has an RMSEP value of 1.5 °C (r^2_{jack} = 0.88) for July air temperature estimates and an RMSEP of 2.2 °C (r^2_{jack} = 0.88) for summer water temperature estimates. Weighted averaging *without* tolerance downweighting (WA) has RMSEP of 1.6 °C (r^2_{jack} = 0.87) for air temperature and RMSEP of 2.6 °C (r^2_{jack} = 0.84) for water temperature (Francis et al., 2006). Two of the 22 subfossil taxa identified in Lake CF8 sediments (Table 1)—*Paracladopelma*, which has a maximum abundance of <2% in down-core samples, and *Metriocnemus fuscipes* type, which has a maximum abundance of <3%—are not represented in the training set and therefore are excluded from these analyses. Notably, all Tanytarsina were lumped together in the statistical analyses in order to achieve taxonomic harmonization with the training set. Four samples—the uppermost and bottommost samples from unit III, and two of the four samples from unit VII—contained fewer than 50 head capsules, but because of the low diversity of these samples, the count sums are likely to be reasonable approximations of their taxonomic compositions.

In order to assess the quality of modern analogs for down-core (fossil) samples, we calculated squared-chord distances (SCDs; Overpeck et al., 1985) between each fossil sample and each sample in the modern training set. SCDs were calculated using program C2 version 1.4.3 (Juggins, 2003). We report the SCD values to each fossil sample's closest modern analog (i.e., the minimum SCD for each fossil sample), and compare that dissimilarity with the 5th and 10th percentiles of the distribution of SCDs for the modern training set. A fossil sample is here considered to have a close modern analog when its minimum SCD is less than the 5th percentile for the training set (Simpson, 2007).

RESULTS

General Character of Chironomid Assemblages

The organic lake sediment units in the core are characterized by very high %LOI and %$BiSiO_2$ and low magnetic susceptibility (MS) compared with the inorganic sand units. The highest %LOI and %$BiSiO_2$ and lowest MS -values

TABLE 1. LIST OF SUBFOSSIL CHIRONOMID TAXA IDENTIFIED IN LAKE CF8 LITHOSTRATIGRAPHIC UNITS

Subfossil taxonomic name	Unit I (Holocene)	Unit III (MIS 5a?)	Unit V (MIS 5)	Unit VII (MIS 7)
Abiskomyia	x			
Chironomus	x		x	
Corynoneura/Thienemanniella	x		x	
Cricotopus/Orthocladius	x		x	x
Eukiefferiella/Tvetenia	x		x	
Heterotrissocladius	x		x	x
Mesocricotopus thienemanni type	x		x	
Metriocnemus fuscipes type		x	x	x
Micropsectra	x		x	x
Oliveridia/Hydrobaenus	x	x	x	x
Orthocladiinae undiff.	x		x	x
Paracladopelma	x			
Parakiefferiella nigra type	x		x	
Paratanytarsus	x		x	
Procladius	x		x	
Protanypus	x		x	x
Psectrocladius	x		x	x
Pseudodiamesa	x		x	
Sergentia	x		x	
Subtribe Tanytarsina undiff.	x		x	x
Tanypodinae undiff.	x		x	
Tanytarsus lugens/Corynocera oliveri type	x		x	

occur within the Holocene sediments. Chironomids were analyzed throughout the organic sediments, and in total, 22 different taxonomic types were enumerated (GSA Data Repository[1]). All but three of these taxa were found in both Holocene and older sediments (Table 1). For comparison, Francis et al. (2006) found a total of 30 chironomid taxa in modern sediment samples from 29 Baffin Island lakes spanning a large geographic area (11° latitude). Throughout the record at Lake CF8, taxonomic assemblages are Arctic in character, containing only taxa that today are common north of tree line (Francis et al., 2006; Barley et al., 2006). Insect remains suggesting forested conditions (e.g., *Glyptotendipes* and *Chaoborus*) are not found in Lake CF8 sediments of any age, in contrast with Fog and Brother of Fog Lakes ~300 km south on east-central Baffin Island, where such taxa were found in Last Interglacial sediments (Francis et al., 2006). At several different times, the assemblage at Lake CF8 has been dominated by the cold stenotherms *Oliveridia*/*Hydrobaenus* and *Pseudodiamesa*, which are taxa associated with extremely cold, ultraoligotrophic lakes (Brooks and Birks, 2004; Francis et al., 2006). Downcore chironomid assemblages and the temperature reconstructions derived from them are discussed in greater detail below, in chronological order from most recent to oldest.

Unit I (Holocene)

Chironomid head capsule concentrations in unit I range from 70 to 550 head capsules per cm^3 of wet sediment. The highest concentrations are in sediments of the earliest Holocene, and chironomids are present from the onset of sedimentation, implying very little delay in initial colonization following deglaciation. Table 1 provides a complete list of chironomid taxa found in this unit. At the onset of lacustrine sedimentation (before 11 ka; Axford et al., 2009b), the cold stenotherm *Oliveridia*/*Hydrobaenus* made up nearly all (>96%) of the chironomid assemblage (Figs. 4 and 5). *Oliveridia*/*Hydrobaenus* was abruptly replaced by an assemblage dominated by the subtribe Tanytarsina (including *T. lugens*/*C. oliveri*), and corresponding inferred temperatures rose rapidly at the onset of the Holocene. The WA model infers colder July air temperatures than the WA_{tol} model (3.4 versus 5.7 °C) for the earliest part of the deglacial period, but it also suggests an earlier transition into full Holocene warmth.

The WA_{tol} and WA models yield similar results for most of the Holocene, although WA_{tol} indicates a more abrupt cooling transition from early to late Holocene, and more dramatic cooling during two brief early Holocene cold events (Fig. 6). Very warm July air temperatures (4–5 °C warmer than present) are inferred by both weighted averaging models for most of the early Holocene, reflecting the abundance of Tanytarsina, Tanypodinae, and *Psectrocladius*, which are qualitative indicators of relatively warm temperatures on Baffin Island (Francis et al., 2006; although the group Tanytarsina in this region may best be described as eurythermic—see, for example, Saulnier-Talbot and Pienitz, 2010). As discussed by Axford et al. (2009b), very warm early Holocene temperatures in the Baffin region are supported by prior paleolimnological studies (e.g., Miller et al., 2005; Briner et al., 2006b), as well as evidence for glacier melting and changes in the northern range limits of marine species (e.g., Dyke et al., 1996; Fisher and Koerner, 2003).

Late Holocene chironomid assemblages are characterized by the disappearance of *T. lugens*/*C. oliveri* and Tanypodinae and greater percentages of taxa with cold affinities, including *Abiskomyia* and the cold stenotherms *Oliveridia*/*Hydrobaenus* and *Pseudodiamesa*. The overall rise of *Oliveridia*/*Hydrobaenus* through the late Holocene suggests progressive cooling. WA_{tol} models fail to reconstruct this additional cooling within the late Holocene, perhaps due to the lack of colder calibration sites in the training set (Axford et al., 2009b); WA models indicate some cooling through the late Holocene and thus appear to perform somewhat better for this period. In the uppermost 2 cm of the record, *Oliveridia*/*Hydrobaenus* and *Pseudodiamesa* both disappear, qualitatively indicating warming; this warming is reflected most clearly in the WA-based temperature reconstructions. The decline and disappearance of the cold stenotherms occurred between A.D. 1950 and 1980, as dated by ^{210}Pb (Thomas et al., 2008).

Unit III

Three chironomid samples were analyzed from unit III, with head capsule concentrations ranging from 50 to 130 heads cm^{-3}. Except for one head capsule of *Metriocnemus fuscipes* type in the deepest sample, all three samples are composed entirely of the cold stenotherm *Oliveridia*/*Hydrobaenus* (Fig. 5; Table 1), which is known to occur in very cold, ultraoligotrophic lakes (e.g., Brooks and Birks, 2004). WA-inferred July air temperatures throughout this unit are ~2 °C. WA_{tol} air temperature inferences from this unit are ~4 °C warmer than that, but they are almost certainly overestimates given the WA_{tol} model's demonstrated inability to reconstruct July air temperatures below 5–6 °C, the cold end of the training set calibration (e.g., Axford et al., 2009b).

Unit V (Last Interglacial)

Head capsule concentrations in unit V sediments range from 15 to 900 heads cm^{-3}, the highest concentrations of the entire record. WA- and WA_{tol}-inferred July air temperatures are warmer than present (preindustrial) beginning at the very bottom of unit V, reflecting the occurrence of relatively thermophilous taxa including *Psectrocladius*, *Procladius*, and other Tanypodinae, and abundant Tanytarsina. The colder inferred temperature for the bottommost sample, relative to samples immediately above, reflects the occurrence of the cold stenotherm *Oliveridia*/*Hydrobaenus* in this sample. Peak inferred temperatures in unit V (4–5 °C warmer than present according to both models) are not significantly different from inferred early Holocene temperatures. During the warmest part of the Last Interglacial, Tanypodinae achieved their maximum abundance of the entire record (Fig. 6), possibly suggesting somewhat warmer conditions than those of the Holocene thermal maximum. Unlike at Fog and Brother of Fog Lakes to the south (Francis et al., 2006), taxa commonly found south of latitudinal tree line in the modern environment do not occur in Last Interglacial sediments of Lake CF8.

WA_{tol}-inferred temperatures drop at 161 cm depth (in core 04-CF8–02; Figs. 4 and 5) in response to the appearance (albeit in very low abundances) of *Pseudodiamesa*, *Parakiefferiella nigra*, and *Mesocricotopus* and then gradually rise again up to 151 cm depth. WA-inferred temperatures without tolerance downweighting do not reflect these subtle changes in the assemblage. Above 151 cm, the cold stenotherms *Oliveridia*/*Hydrobaenus* and *Pseudodiamesa* appear and then increase in abundance, and WA_{tol}-inferred temperatures drop precipitously. WA-inferred temperatures drop slightly farther up in the section, at 143 cm, again displaying less sensitivity to the presence of cold indicator taxa with very low abundances. *Sergentia*, *Micropsectra*, and *Pseudodiamesa* dominate the assemblage in the upper half of the unit, *T. lugens*/*C. oliveri* declines, and *Psectrocladius* and Tanypodinae disappear. Differences between WA- and WA_{tol}-inferred temperatures are lowest in the bottom third of unit V, where both methods predict very warm temperatures, and in the upper three samples, which have lower inferred temperatures.

[1]GSA Data Repository item 2011044, Chironomid assemblage data from Lake CF8, Baffin Island, Canada, is available at http://www.geosociety.org/pubs/ft2011.htm or by request to editing@geosociety.org.

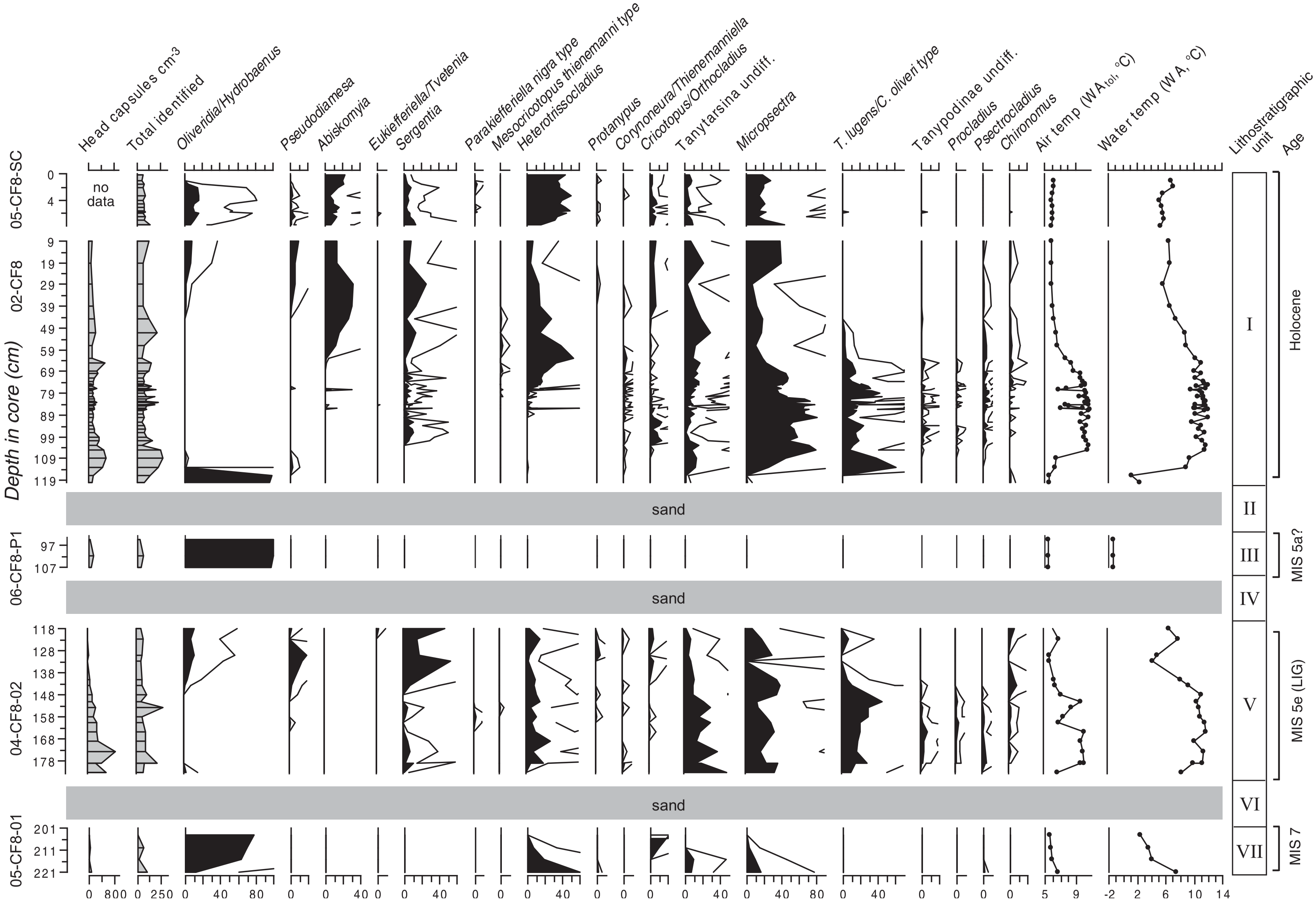

Figure 5. Chironomid stratigraphic diagram, showing head capsule concentrations (in whole head capsules per cm³), number of whole head capsules identified per sample, percentages of chironomid taxa, inferred July air temperatures using WA_{tol} model, and inferred summer water temperatures using WA model for each of the four gyttja units recovered from Lake CF8. Taxa are ordered by temperature optima with coldest on the left (from Francis et al., 2006), except *Micropsectra* and *Tanytarsus lugens*/*Corynocera oliveri*, for which optima are unknown. Unfilled lines are 5× exaggerations. Only taxa that make up at least 2% of at least one sample are shown. Table 1 provides a complete list of all taxa found in Lake CF8 sediments, and data are online as GSA Data Repository Table DR1 (see in-text footnote 1). The WA_{tol} air temperature model has root mean squared error of prediction (RMSEP) of 1.5 °C, and the WA water temperature model has RMSEP of 2.6 °C. Analyses are from five different cores (see Fig. 3) with independent depth axes, shown on the left. Depth axis for the surface core (05-CF8-SC, uppermost Holocene sediments) is stretched for clarity. Lithostratigraphic units and their inferred ages are shown on the right. MIS—marine oxygen isotope stage; LIG—Last Interglacial.

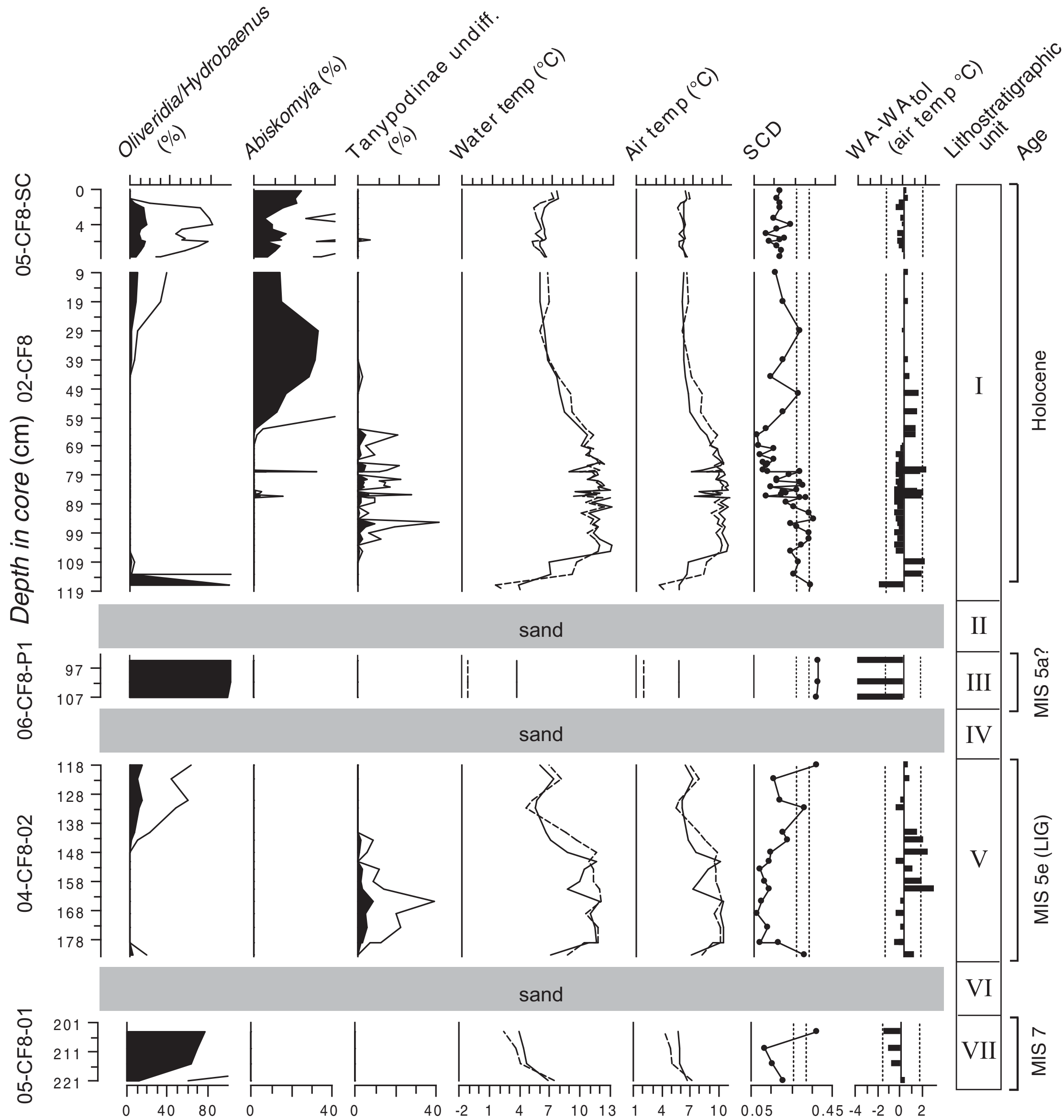

Figure 6. Percentages of *Oliveridia/Hydrobaenus* (a cold stenotherm), *Abiskomyia*, and Tanypodinae (an indicator of relative warmth); summer water temperatures inferred using WA_{tol} (solid gray line, RMSEP 2.2 °C) and WA (dashed black line, RMSEP 2.6 °C) models; July air temperatures inferred using the WA_{tol} (solid gray line, RMSEP 1.5 °C) and WA (dashed black line, RMSEP 1.6 °C) models; squared-chord distances (SCDs) to each sample's closest modern analog, with the 5th and 10th percentiles from the training set shown as dotted vertical lines; and differences between WA_{tol}- and WA-inferred air temperatures (differences beyond the dotted line exceed model RMSEP). Analyses are from five different cores (see Fig. 3) with independent depth axes, shown on the left. Depth axis for the surface core (05-CF8-SC, uppermost Holocene sediments) is stretched for clarity. Lithostratigraphic units and their inferred ages are shown on the right. MIS—marine oxygen isotope stage; LIG—Last Interglacial.

Unit VII (Penultimate Interglacial, MIS 7)

Head capsule concentrations in unit VII range from 5 to 95 heads cm^{-3}. The inferred July air temperature for the bottommost sample in this unit (~7 °C) is comparable to some samples in the mid- to late Holocene. Assemblages in the three upper samples in unit VII imply steadily declining temperatures. Inferred temperatures at the top of this unit are cooler than for any Last Interglacial or late Holocene samples, reflecting low percentages of thermophilous taxa. There are significant assemblage changes within the portion of MIS 7 recorded by unit VII, notably the shift from dominance of *Heterotrissocladius* to *Oliveridia/Hydrobaenus* and the corresponding decline in inferred temperatures. As in unit III, inferred temperatures from most samples in unit VII are at the low end of the training set's calibration range, and WA-inferred temperatures are likely overestimates.

Comparisons between Temperature Inference Models

Figure 6 compares results of four temperature inference models applied to Lake CF8 chironomid assemblages. Tolerance downweighting is a common practice giving greater weight to important indicator taxa (i.e., taxa with narrow environmental tolerances) that may occur in low relative abundances. Fifty-eight of the 70 down-core samples in our study exhibit differences between WA- and WA_{tol}-inferred temperatures of <1.6 °C; in other words, the two methods predicted temperatures within the model RMSEP of each other for 83% of the down-core samples. Two types of assemblages exhibit larger differences between methods: Samples containing small percentages of cold stenothermous indicator taxa (i.e., less than 5% of taxa such as *Oliveridia*/*Hydrobaenus*, *Pseudodiamesa*, *Parakiefferiella nigra*, and *Mesocricotopus*) exhibit large positive differences (i.e., significantly colder WA_{tol}- versus WA-inferred temperatures). In contrast, samples heavily dominated by cold indicator taxa, and thus qualitatively suggesting temperatures much colder than present, have large negative differences (i.e., WA_{tol}-inferred temperatures significantly warmer than those inferred without tolerance downweighting). All of the samples with negative differences >1.6 °C also have relatively poor analogs in the modern training set, suggesting that they will be inherently problematic for quantitative temperature reconstruction using the available models. Air and water temperature reconstructions exhibit very similar trends over time, although inferred water temperatures undergo larger absolute temperature changes, consistent with the larger range of observed water (versus air) temperatures at the calibration sites (Francis et al., 2006).

DISCUSSION

Modern Analogs and Persistence of Assemblages through Time

The application of modern calibration data to ancient sediments presents the potential for "no-analog" subfossil assemblages, as well as past morphological and ecological changes within species (e.g., Brooks, 2006; Williams and Jackson, 2007). However, the antiquity of fossil assemblages at Lake CF8 does not predict whether they will have close modern analogs. Indeed, many ancient assemblages from the Last Interglacial and even MIS 7 have closer analogs in the modern environment than some Holocene assemblages. Based upon SCD measurements (Fig. 6), most samples from the mid- to late Holocene, Last Interglacial, and MIS 7 have close analogs in the calibration data set (i.e., minimum SCDs less than the 5th percentile from the training set). The closest modern analogs for mid- to late Holocene and late Last Interglacial samples are sites on northern Baffin Island (Walker et al., 1997; Francis et al., 2006). Early Holocene and early Last Interglacial samples have closest modern analogs on southern Baffin Island and ~1600 km farther south in central and northern Labrador. For example, several Last Interglacial samples have a closest modern analog in 5-m-deep Lake 42 (Walker et al., 1997), 150 km from the Atlantic coast in Labrador at 54.8°N (Fig. 2). The oldest sample in the core, from the deepest MIS 7 sediments we recovered, has its closest modern analogs in northern Labrador, at ~57.3°N, south of the Torngat Mountains.

The samples with the largest SCDs, i.e., most problematic analogs, are the coldest samples: samples from the unit III interstadial, the late-glacial period preceding the onset of early Holocene warmth, and the final stages of MIS 7 and the Last Interglacial, when climate cooled toward glacial conditions. Given that none of the modern calibration sites is significantly colder than Lake CF8 today, the lack of close analogs for assemblages during periods colder than present is unsurprising.

Some samples from the warm early Holocene also lack close analogs. This might seem to suggest that the early Holocene assemblages, which are heavily dominated by the subtribe Tanytarsina, could be pioneering assemblages that reflect either a long lag in postglacial colonization or long-term ecological impacts of postglacial lake ontogeny. However, a long lag in colonization seems very unlikely, given widespread evidence for rapid dispersal and colonization by chironomids, including the diverse assemblage preserved at Lake CF8 from the early part of MIS 5e. Geologic evidence indicates that the Laurentide Ice Sheet accomplished very little erosional or depositional modification of Lake CF8 or the surrounding landscape (Briner et al., 2003, 2007), which may argue against extensive postglacial ontogenetic changes in the lake environment. The existence of close analogs for early Last Interglacial samples, which do not exhibit such extreme dominance by Tanytarsina, further argues against both of these possibilities. On the other hand, a similar early Holocene phase of Tanytarsina-dominated assemblages has been documented at nearby Lake CF3 (Briner et al., 2006b) and in lakes on the Ungava Peninsula just south of Baffin Island (Saulnier-Talbot and Pienitz, 2010; Fig. 2). It has been suggested that the dominance of Tanytarsina in early postglacial sediments in this region might represent a phase of postglacial succession (Saulnier-Talbot and Pienitz, 2010). If so, it is interesting that the onset of the Last Interglacial at Lake CF8 was not quite so conspicuously dominated by Tanytarsina.

The chironomid faunas preserved in the Holocene and older interglacial sediments are very similar in character, with few major differences in terms of the taxa present (Table 1). The most notable exception is *Abiskomyia*, which is abundant throughout much of unit I and in modern sediments from the lake but is conspicuously absent from all pre-Holocene sediments. *Abiskomyia* is also abundant in Holocene but is absent from Last Interglacial sediments from lakes on east-central Baffin Island (Francis et al., 2006), suggesting that it may be a recent immigrant to the region, consistent with its limited geographic distribution today (e.g., Gajewski et al., 2005). *Paracladopelma* is rare but present (maximum abundance <2%) in Holocene sediments from Lake CF8, and like *Abiskomyia*, it is absent from older units. *Metriocnemus fuscipes* type was found only in the pre-Holocene units. All other identified taxa were found in both Holocene and older units at Lake CF8 (see Table 1). Overall, despite intervening glaciations, which must have extirpated most or all chironomid species from the region, the chironomid fauna of MIS 7, the Last Interglacial, and the Holocene were very similar at Lake CF8. This suggests remarkable stability of northern Baffin Island interglacial chironomid faunas through the late Quaternary, and the ability of chironomids to rapidly repatriate landscapes after deglaciation.

Climate of the Penultimate Interglacial (MIS 7)

Geophysical surveys indicate that coring did not penetrate to the base of MIS 7; future efforts in the field might capture older sediments. The bottommost MIS 7 sample we analyzed contains a relatively diverse chironomid assemblage, and both weighted averaging methods predicted air temperatures of ~7 °C. The oldest sediments recovered from Lake CF8 appear to record a time when summer temperatures were slightly warmer than the preindustrial late Holocene. This is consistent with prior studies showing near-modern temperatures over parts of MIS 7 (e.g., de Vernal and Hillaire-Marcel, 2008). The younger MIS 7 sediments record a gradual decline into temperatures more comparable to late-glacial times, presumably followed by glacial conditions and a hiatus in deposition that lasted until the penultimate deglaciation (i.e., Termination 2).

Climate of the Last Interglacial

Extreme Last Interglacial warmth in the Baffin Bay region, compared with other parts of the Northern Hemisphere and even other parts of the Arctic, is hypothesized to have resulted from strong amplification of insolation-driven warming by cryospheric (e.g., sea-ice) and land-cover feedbacks (CAPE Last Interglacial Project Members, 2006), similar to those that are accelerating warming in the Arctic today (e.g., Overpeck et al., 1997; Chapin et al., 2005; Serreze et al., 2009). Paleotemperature records from luminescence-dated Last Interglacial lake sediment sequences on Baffin Island south of the Clyde region reveal a Last Interglacial temperature anomaly at least as large as at Lake CF8, and in some cases larger (Miller et al., 1999; Wolfe et al., 2000; Francis et al., 2006; Fréchette et al., 2006). Chironomid data from Fog and Brother of Fog Lakes on the Cumberland Peninsula (Fig. 2) record peak Last Interglacial air temperatures as much as 7–8 °C warmer than present, and Last Interglacial sediments from both lakes contain thermophilous chironomids and *Chaoborus* (Chaoboridae) that are not seen in the Holocene (Francis et al., 2006). Pollen data indicate that summers during the peak of the Last Interglacial were 3–5 °C warmer than today, with Last Interglacial sediments at Fog Lake containing higher percentages of shrub (*Alnus* and *Betula*) pollen than Holocene sediments (Fréchette et al., 2006).

Unlike these records from farther south on Baffin Island, the chironomid data from Lake CF8 suggest that summer temperatures through much of the early Holocene were comparable to the warmth of the Last Interglacial. This contrasts with the higher sea level documented for MIS 5e relative to the Holocene (e.g., Koerner, 1989; Cuffey and Marshall, 2000; Muhs, 2002; CAPE Last Interglacial Project Members, 2006; Otto-Bliesner et al., 2006; Overpeck et al., 2006), and with the observation that maximum Arctic summer insolation during the Last Interglacial coincided with relatively protracted ice-sheet extent (compared with the Holocene insolation maximum) and thus drove a larger temperature response (CAPE Last Interglacial Project Members, 2006). The apparent discrepancy between Lake CF8 chironomid-inferred Last Interglacial temperatures and other paleoclimate records may reflect real spatial heterogeneity in the expression of Last Interglacial warmth across the Arctic. Alternatively, early Holocene temperature reconstructions from Lake CF8 may be overestimates, perhaps because many of the early Holocene samples do not have close analogs in the modern calibration data, whereas Last Interglacial samples appear to have very good analogs. However, significant early Holocene warmth in this region is supported by other records, including melt on Agassiz Ice Cap (Fisher and Koerner, 2003). A third possibility, and the explanation we favor, is that chironomid assemblages at Lake CF8 may not have registered the full extent of Last Interglacial warmth. Tree line is a major ecological threshold for chironomids (e.g., Walker and Mathewes, 1989; Walker, 1990; Walker and MacDonald, 1995), and some of the fossil chironomid taxa that suggest very warm Last Interglacial temperatures at east-central Baffin Island lakes are taxa that today live south of latitudinal tree line (Francis et al., 2006). Shrubification or afforestation of more southern sites under Last Interglacial warmth would have allowed for immigration of these chironomid taxa, whereas Lake CF8 farther north may not have offered appropriate habitat for these taxa. Additional independent proxy data from Lake CF8 (e.g., pollen, organic geochemistry) would help with interpreting this discrepancy between Last Interglacial paleotemperature reconstructions from Lake CF8 and other sites.

Despite these caveats regarding absolute temperature estimates for the Last Interglacial, the Lake CF8 record is unusual in that it preserves temporal structure within the Last Interglacial. Chironomid assemblages record full-interglacial temperatures at the onset of Last Interglacial lacustrine deposition, implying that relatively warm temperatures were already established at the time of local deglaciation. In contrast, the Holocene experienced a more prolonged ramp-up of temperatures after deglaciation, as indicated by very cold temperatures inferred for the deepest unit I sediments. Lake CF8 chironomids also suggest a cold reversal within the period of peak Last Interglacial warmth. Peak Last Interglacial warmth at Lake CF8 was later followed by a final descent into colder temperatures, which persisted at the site for some time before lacustrine sedimentation ceased with the descent into glacial conditions. The temperature record inferred from Lake CF8 is thus consistent with the observation that peak Last Interglacial warmth ended thousands of years before sea level dropped below (i.e., global ice volume exceeded) modern-day values (Zagwijn, 1996).

The observed pattern of early warmth followed by subsequent cooling is similar to many records that span MIS 5e (e.g., Petit et al., 1999; McManus et al., 2002; EPICA Community Members, 2004). The structure and amplitude of millennial-scale Last Interglacial temperature changes at Lake CF8 were apparently similar to those of the Holocene. The thickness of unit V (Last Interglacial) is also similar to that of unit I (Holocene), especially after accounting for compaction of unit V, which can be estimated based upon unit V's lower moisture content and greater density (Axford, 2007): The dry mass accumulation (per cm^2) represented by units V and I are very similar (Axford et al., 2009a). These observations support the hypothesis that unit V sediments record only MIS 5e, i.e., the Last Interglacial sensu stricto. However, we cannot rule out the possibility that unit V records a longer interval of MIS 5, e.g., part or all of 5d and 5c in addition to 5e.

Evidence for MIS 5 Ice-Sheet Fluctuations

The three radiocarbon ages from unit III (reported by Briner et al., 2007) are nonfinite, indicating that this unit is older than ca. 48 ka. Unit V (MIS 5e) provides a maximum limiting age. We therefore correlate unit III with either MIS 5c or 5a, the two periods of smallest global ice volume (Martinson et al., 1987) and highest summer insolation at northern latitudes (Berger and Loutre, 1991) between MIS 5e and 48 ka. Unit III and the underlying sand unit together provide evidence for an ice-sheet advance and subsequent retreat during MIS 5. Such an advance has long been hypothesized (Miller et al., 1977; Miller and deVernal, 1992; Marshall, 2002; Yoshimori et al., 2002; Ruddiman et al., 2005), but CF8 sediments provide rare direct evidence and constraints on ice extent: Ice had to advance at least as far as the lake to deposit sands from an ice-marginal meltwater channel (the lake is situated well above local river valleys, implying a local source for the sands), and later retreated behind the lake to allow for deposition of lake sediments including lacustrine microfossils in unit III. Based on the chironomid assemblage, temperatures were significantly colder than today. Deposition of organic lake sediments in unit III, coupled with the presence of chironomids, diatoms, and bryophytes, indicates conditions in which the lake had at least an ice-free moat for part of the summer.

Holocene sediments overlying Last Interglacial sediments have been recovered from several lakes on Baffin Island (Wolfe et al., 2000; Miller et al., 2002; Francis et al., 2006; Fréchette et al., 2006), but in contrast, those lakes contain no evidence for viable lake ecosystems during an intervening interstadial period. These lakes sit at 360–848 m above sea level (asl), higher elevations than Lake CF8. It is possible that they remained covered by glacier ice, or at least perennially frozen, despite deglaciation of the ice-distal, low-lying Clyde Foreland.

Twentieth Century in Context of the Past 200,000 Years

Thomas et al. (2008) discussed the mid-twentieth-century extirpation of cold stenothermous chironomid taxa from Lake CF8, and pointed out that this significant faunal change and the associated reconstructed warming are unprecedented for this site over the past 5000 yr. This begs the question of whether twentieth-century warming and faunal assemblage shifts are unprecedented over longer time scales. The long record presented here reveals that, over the past 200,000 yr, extended periods warmer than the latter half of the twentieth-century were rare. Only the insolation-driven peaks of the Last Interglacial and the early Holocene thermal maximum were warmer, and these were the only other periods of the past 200,000 yr during which both *Oliveridia*/*Hydrobaenus* and *Pseudodiamesa* were absent from the lake. Recent chironomid-inferred temperatures at Lake CF8 are thus not unprecedented over the period of record, but they only have analogs during two periods that experienced enhanced Northern Hemisphere insolation forcing relative to today. Examining a broader multiproxy data set derived from the Lake CF8 sediments discussed here, Axford et al. (2009a) found that, collectively, the combined biological and geochemical changes (from shifts in diatom and chironomid assemblages to organic carbon sources) that occurred at this site during the twentieth-century are indeed unique within the past 200,000 yr.

CONCLUSIONS

Paleoecological data from Lake CF8 demonstrate that sediments preserved beneath cold-based portions of Pleistocene ice sheets can record changing climate and environmental conditions throughout multiple interglacial periods. Chironomid remains in Lake CF8 are well preserved in 200,000-yr-old sediments, providing an Arctic paleotemperature record that extends further back in time than the Greenland ice-core records. Ancient chironomid assemblages at Lake CF8 (except for during the coldest periods) have close analogs in modern calibration data from northeastern North America. There is no deterioration in the quality of modern analogs with age of fossil assemblages from Lake CF8. In fact, Last Interglacial assemblages on average have closer modern analogs, as determined by squared-chord distance, than fossil assemblages from the Holocene. Taxa show remarkable persistence over time, with little difference between interglacials in terms of the particular taxa present despite intervening periods of continent-scale glaciation. A notable exception is *Abiskomyia*, a late immigrant that did not appear at Lake CF8 until the Holocene.

Temperature reconstructions based upon weighted-averaging models indicate that three periods of the past 200,000 yr experienced summer temperatures warmer than the preindustrial late Holocene on Baffin Island: the early Holocene, the early part of the Last Interglacial (MIS 5e), and some portion of MIS 7, the penultimate interglacial period. The early Holocene and MIS 5e also experienced temperatures warmer than those reconstructed for the late twentieth century at Lake CF8. Warmth during these periods correlates with known positive anomalies in summer solar insolation that were most pronounced at high northern latitudes. Reconstructed MIS 5e air temperatures were 4–5 °C warmer than preindustrial late Holocene temperatures, but unlike many records from the Arctic, the Lake CF8 chironomid record does not clearly indicate that MIS 5e was warmer than the early Holocene. This discrepancy, which we hypothesize could be related to vegetation dependence of the adult phase for some chironomid species, should be investigated with additional, independent proxy data from Lake CF8 sediments or other archives. The Lake CF8 sediment record provides direct evidence for a long-hypothesized ice-sheet advance and subsequent retreat (regional deglaciation) during MIS 5.

Major climate trends *within* the three past interglacial periods, extending to the present decade, are also recorded by chironomid assemblages from Lake CF8. For example, chironomid assemblages record the descent into glacial conditions following both MIS 7 and MIS 5e, as well as twentieth-century warming that recently interrupted the insolation-driven cooling trend inferred through the late Holocene. This unusual sedimentary archive and the chironomid remains preserved within it provide a rare long-term perspective on terrestrial conditions in the Arctic, a sensitive region that plays an important role in global climate change.

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