

Postglacial chironomid assemblage succession in northernmost Ungava Peninsula, Canada

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ABSTRACT: Sediment cores spanning the postglacial period were recovered from two coastal freshwater basins located 300 km apart in northernmost Ungava (Nunavik, Canada). A basal date from the sequence recovered near Wakeham Bay suggests that the region was ice-free by as early as 9600 cal. a BP. The initial development of both investigated lacustrine ecosystems was characterised by chironomid assemblages strongly dominated by the Subtribe Tanytarsina. These early postglacial assemblages showed greatly reduced diversity but much greater abundance than during subsequent periods of lake evolution. An abrupt and distinct turnover in sedimentary chironomid assemblage composition and productivity, marked by a switch to a dominance of Orthoclaadiinae, occurred around 6 ka BP. This turnover likely corresponds with a significant disturbance in the regional environment, which could be linked to the final disappearance of the last remnants of the Laurentide Ice Sheet. These findings, based on the first palaeolimnological investigations undertaken in northernmost Ungava, provide new insights into lateglacial and postglacial faunal recolonisation patterns in aquatic ecosystems of the eastern Canadian Arctic. Copyright © 2009 John Wiley & Sons, Ltd.



KEYWORDS: lakes; sediments; sedimentary chironomids; Subtribe Tanytarsina; deglaciation; northern Ungava.

Introduction

Chironomids (Insecta: Diptera) are among the most diverse, abundant and widely distributed insects in the Canadian Arctic (Oliver, 1968). The northern tree line does not seem to be an important zoogeographical barrier to their northward spread and their high diversity has been reported from the wet tundra habitats of northern Canada (Oliver and Dillon, 1997). Winged adults are mobile and have a short lifespan (a few days to a week), which implies they have the potential to respond rapidly to environmental change. The chitinous remains of the aquatic larvae of chironomids are generally well preserved in lake sediments and are now routinely used as indicators in the framework of palaeoenvironmental studies in arctic regions (e.g. Walker, 2001; Pienitz *et al.*, 2004; Brooks, 2006; Walker and Cwynar, 2006). Fallu *et al.* (2005) provided the first reconstruction of postglacial summer surface-water temperatures in northern Quebec–Labrador using a previously developed inference model (transfer function) for eastern Canada (Walker *et al.*, 1997). However, basic questions concerning the dynamics and early postglacial succession of sedimentary chironomid assemblages, their abundance and the level of

primary productivity in the postglacial lacustrine environment of this region have not yet been addressed.

In this study, we present the postglacial sedimentary sequences of two lakes located approximately 300 km apart in northernmost Ungava, in which the chironomid assemblages of the initial lake phases (i.e. following the retreat of the Laurentide Ice Sheet, LIS) were dominated by the genera *Micropsectra* (Kieffer 1909), *Tanytarsus* (van der Wulp 1874), *Corynocera* (Zetterstedt 1838) and *Cladotanytarsus* (Kieffer 1921), referred to collectively as Subtribe Tanytarsina (Saether, 1977). The aim of this study was to interpret the initial dominance of the Subtribe Tanytarsina within the context of early postglacial environmental development in northernmost Ungava. We therefore explore the relationships between the sedimentary chironomid assemblages, absolute abundances of chironomid head capsules, siliceous algal (diatom) diversity, amount of biogenic silica and organic matter content as determined by loss-on-ignition (LOI), and compare our findings to similar cases reported from other eastern Canadian Arctic sites.

Study area (Fig. 1) and its deglacial chronology

The northern Ungava coast consists of granitic gneisses of Archean age belonging to the Lake Superior and Churchill structural provinces, where Quaternary deposits are generally represented by thin and sparse tills (Gray and Lauriol, 1985;

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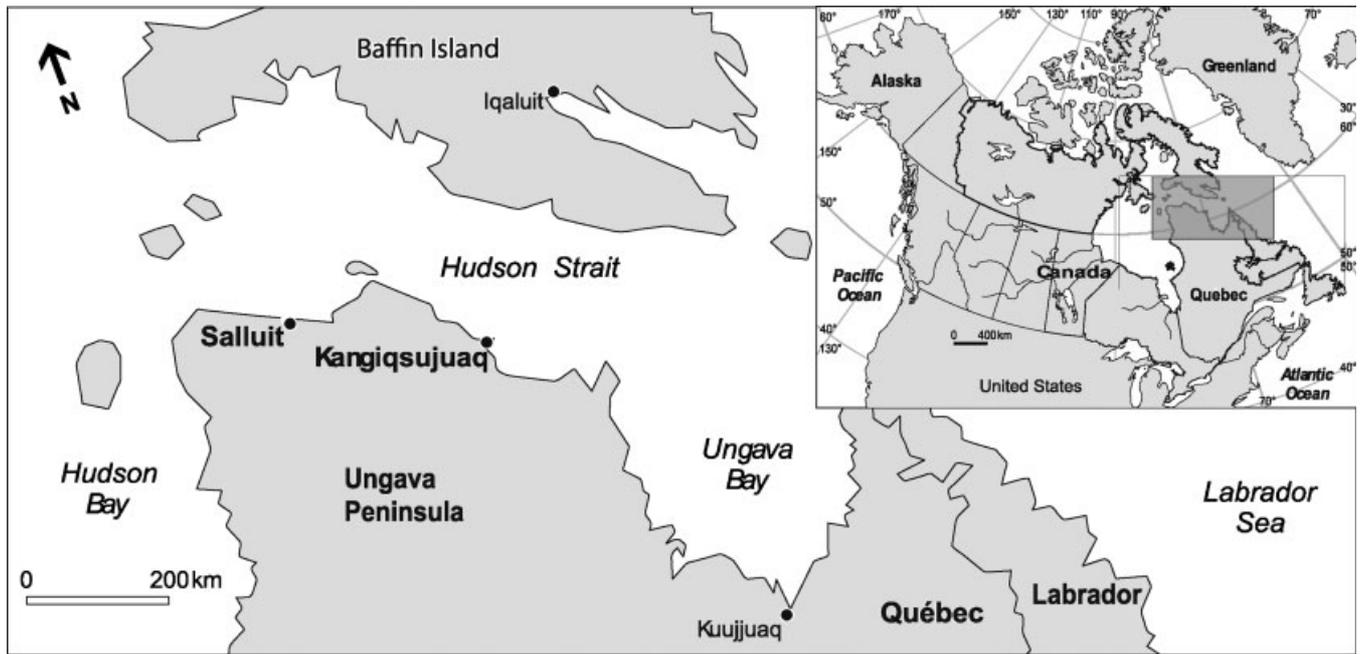


Figure 1 Map showing the location of the two study sites in northern Ungava (Québec, Canada)

Daigneault and Bouchard, 2004). Average plateau altitudes on the fjord-indented coast of southern Hudson Strait vary between 200 and 400 m above modern sea level (a.s.l.). Geomorphological features show a northerly ice flow pattern (Daigneault and Bouchard, 2004, and citations therein) and suggest glacial withdrawal from the Hudson Strait coast towards the interior (i.e. from north to south) (Gray and Lauriol, 1985; Lauriol and Gray, 1987). Previous studies place the time of deglaciation along the southern shore of Hudson Strait between 10.5 and 8 ka BP, with possible (although controversial in interpretation) readvances around 9.9 ka BP (Gold Cove Advance) and 8.7 ka BP (Noble Inlet Advance) (reviewed in Andrews *et al.*, 1995; Gray, 2001). Postglacial land emergence in the sector between Cape Wolstenholme and Deception Bay (Salluit sector) was characterised by a phase of rapid initial isostatic rebound averaging about $8 \text{ m } 100 \text{ a}^{-1}$ until 5200 ^{14}C a BP, followed by a period of much slower uplift with average rates $<0.3 \text{ m } 100 \text{ a}^{-1}$ (Matthews, 1966, 1967). The regional maximum postglacial marine limit reached 150 m a.s.l. in the nearby valley of the Foucault (Narsajuaq) River (Kasper and Allard, 2001). In the Kangiqsujaq region, no data are available for postglacial isostatic rebound and there is only limited knowledge concerning marine limits. Nichols (1936) observed a minimal postglacial marine limit at 33.5 m a.s.l. in the vicinity of Wakeham Bay (now Kangiqsujaq), as indicated by the presence of foraminifer-rich clays. However, Gray and Lauriol (1985) later evaluated the marine limit in this sector to be much higher, around 127 m a.s.l.

According to geomorphological observations made in the northernmost sector of the Ungava Peninsula, it is believed that outlet glaciers and ice tongues emanating from the plateau ice cap occupied deeply entrenched glacial valleys that were in contact with tidewater in the fjords until 6700 ^{14}C a BP (Matthews, 1963; Lauriol and Gray, 1987). According to these authors, the proposed stationary nature of the ice front would be explained by local climate, which was characterised by cold humid summers and abundant snowfall in winter, permitting late summer survival of numerous snow banks and stabilisation of the glacial front beyond 7000 ^{14}C a BP (Lauriol and Gray, 1987). Furthermore, the oxygen isotopic signal in marine molluscs from the littoral of northern Ungava also suggests that meltwater derived from continental deglaciation affected the area until ca. 6000 ^{14}C a BP (Lauriol and Gray, 1997). Finally,

Lauriol and Gray (1987) propose that the last remnants of the ice sheet persisted on the plateau until about 5000 ^{14}C a BP.

The two study lakes, lac de l'Aéroport and Nipingngajulik, are located near the Inuit communities of Salluit and Kangiqsujaq, respectively (Fig. 1). In northernmost Ungava, ice cover usually forms on the lakes in late October/early November and melt-out occurs during June. Mean annual diurnal air temperatures recorded at Salluit and Kangiqsujaq airports between 1992 and 2004 were -7.7°C and -6.3°C , respectively (see Saulnier-Talbot *et al.*, 2007). Means for the three warmest months (June, July, August) were 6.2°C and 7.8°C , whereas they were -24.3°C and -21.7°C for the three coldest months (January, February, March), respectively. More detailed hydroclimatic data for the region are presented elsewhere (Bouchard, 2005; Saulnier-Talbot *et al.*, 2007).

The study region is part of the Mid-Arctic vegetation zone (Edlund, 1984). The catchments of the two study lakes are sparsely vegetated by grasses, mosses and lichens. Lac de l'Aéroport (unofficial name) is located at $\sim 220 \text{ m a.s.l.}$, adjacent to the landing strip of Salluit airport. Conductivity, oxygen and thermal profiles suggest that the water column is well mixed throughout the year. Average values for these and other parameters are given in Table 1. Nipingngajulik is located a few kilometres east of the village of Kangiqsujaq, at $\sim 125 \text{ m a.s.l.}$ Measured pH varied between 5.8 under the ice cover in May 2003 and 6.7 at the lake's surface during early September 2004. In autumn, dissolved O_2 and pH showed values that decreased respectively from 14.17 mg L^{-1} and 6.7 at the lake's surface to 12.71 mg L^{-1} and 6.1 at 10 m depth. However, the thermal and conductivity profiles displayed homogeneous conditions throughout the water column.

Methods

Coring and sediment chronology

Two cores were retrieved from 8.6 m water depth in the central part of ice-covered lac de l'Aéroport in early April 2002. The upper 20 cm of sediments were extruded by use of a gravity

Table 1 General environmental and limnological characteristics of the two study sites

Lake name Locality Coordinates	Altitude (m a.s.l.)	Max. depth measured (m)	Surface area (km ²)	Surface pH	Surface conductivity (mS cm ⁻¹)	Dissolved O ₂ (mg L ⁻¹) ^a	Water temp. (°C) (A) Summer 2002 (B) Sept. 2004
lac de l'Aéroport Salluit 62° 10' 41" N, 75° 39' 48" W	220	8.6	0.0387	6.8	0.072	12.3	(A) 8–12 (B) 4.5
Nipingngajulik Kangiqsujuaq 61° 34' 16" N, 71° 46' 06" W	125	14.5	0.7925	5.8–6.7	0.23	14.0	(A) n/a (B) 4.3

^a The value given for lac de l'Aéroport is valid only for the surface waters, whereas the value for Nipingngajulik represents the mean for the top 10 m of the water column. Measurements of pH, conductivity and dissolved O₂ were taken during September 2004.

corer and subsampled vertically in the field into 0.5 cm thick slices (the water–sediment interface was undisturbed in this core). The deeper sediments were extruded using a modified Livingstone piston corer (Livingstone, 1955). Due to extremely cold air temperature (around –50°C) during fieldwork, the sediments in the metal piston corer froze almost instantly after retrieval, making it impossible to subsample *in situ*. Instead, the core was transported vertically back to the village and extruded following thawing. Owing to their watery nature, the stratigraphy of the uppermost surface sediments was lost and the total length of this core was initially estimated to be 47 cm. However, because the more consolidated sediments were undisturbed, the matching/correlation of the two cores was possible based on LOI, total sedimentary diatom, chironomid and chrysophyte abundance, as well as diatom and chironomid assemblage composition (relative species abundances). The overall length of the recovered sediment sequence was thus calculated to be 50 cm. The central part of Nipingngajulik was cored at 14.5 m water depth in early May 2003 from the ice cover. A 32 cm long sediment sequence was retrieved using a Glew gravity corer. It was subsampled vertically in the field, as described above. The sediment samples from all cores were kept cool and in the dark in plastic bags until lyophilisation.

The chronology of the sediment cores was established using ¹⁴C accelerator mass spectrometry (AMS) dating techniques. Due to the absence of macrofossils of sufficient size, humic acid extracts (HA) were dated following the method of Abbott and Stafford (1996). The extractions were performed at Université Laval's Radiocarbon Laboratory and the resulting combusted CO₂ gas was dated at the Keck Carbon Cycle AMS Facility (UC Irvine, California). More details about methods employed for establishing core chronologies are given in Saulnier-Talbot *et al.* (2009).

Chironomid primary data

Standard methods were used to isolate sedimentary chironomid remains (Walker, 2001). Briefly, a measured amount of freeze-dried sediment (0.1–2.0 g) was rehydrated and deflocculated in warm 5% KOH for approximately 20 min, then rinsed through a 74 µm mesh sieve. The remaining fraction was transferred into a Bogorov counting tray (Gannon, 1971) and the sedimentary chironomid remains were sorted under 40× magnification and mounted permanently onto microscope slides using either Entellan[®] or Clearmount[®]. The head capsules were examined under 200–400× magnification and identified in accordance with Wiederholm (1983) and Walker (1988, 2000). A minimum of 50 head capsules was sorted from each level (Heiri and Lotter, 2001; Larocque, 2001; Quinlan and Smol, 2001); those including more than half of the mentum were counted as one

specimen, whereas halves were counted as such and fragments representing less than one half were discarded.

To confirm the major trends of taxonomic variation and to assess compositional turnover among the stratigraphic samples in each core, we applied indirect gradient analysis (Hill and Gauch, 1980) implemented using the software CANOCO (ter Braak and Smilauer, 1997–2003) to square-root transformed relative abundances of chironomids.

Other sedimentary data

Sediments were processed for siliceous sedimentary extraction by digesting ~40 mg of dry sediment with 5 mL of 30% H₂O₂ for 24 h, then heating for approximately 2 h until the reaction was complete and the solution clear (Battarbee *et al.*, 2001). Siliceous slurries were then rinsed with distilled H₂O until the pH was circumneutral and mounted onto microscope slides using Naphrax[®]. The amount of biogenic silica (BSi) was measured at the Amino Acid Geochronology Laboratory (Northern Arizona University). BSi was extracted from the sediment with 10% Na₂CO₃ and the concentration was determined with a spectrophotometer following the procedure of Mortlock and Froelich (1989). Measurement of organic matter content by LOI was performed at 550°C following standard methods outlined in Heiri *et al.* (2001).

Plotting of results

Relative abundances (%) of chironomid taxa, first DCA axis, absolute abundances of the various sedimentary indicators, BSi (mg g⁻¹) and LOI (%) were plotted stratigraphically using the software C2 version 1.5 (Juggins, 2003). Only chironomid taxa with a relative abundance of at least 5% in one sample were included in the figures. Species diversity is expressed as Hill's N₂, an index which describes the effective occurrence of species in a sample and is sensitive to the changes in the abundance of common species (Hill, 1973; Peet, 1974).

Results

Core chronology

The silty or silty–clayey sediments at the bottom of the sedimentary sequences are likely of glacio-lacustrine origin and suggest that the entire postglacial sequence was retrieved in both lakes. The results obtained by AMS ¹⁴C dating of humic

Table 2 Results of AMS ^{14}C analyses performed on sedimentary humic acids from lac de l'Aéroport and Nipingngajulik, northern Ungava

Lake code and depth (cm) of sample	AMS lab #	$\delta^{13}\text{C}$	\pm	Fraction modern	\pm	$\delta^{14}\text{C}$ (per mil)	\pm	Conventional age (^{14}C a BP)	\pm	Corrected age (^{14}C a BP)	\pm	Calibrated age range (cal. a BP)	\pm
AER 11.5–12	UCI-28791	-22.6	0.6	0.7316	0.0012	-268.4	1.2	2550	18	2250	300	1542 (2250)	2957 708
AER 22–22.5	UCI-21737	-22.0	0.2	0.4888	0.0009	-511.2	0.9	5800	20	5500	300	5607 (6281)	6955 674
AER 29–29.5	UCI-24214	-20.0	0.9	0.4171	0.0009	-582.9	0.9	7110	25	7110	30	7872 (7923)	7974 51
AER 36–36.5	UCI-21584	-23.3	0.8	0.4079	0.0012	-592.2	1.2	7230	28	7230	30	7974 (8066)	8157 92
AER 49.5–50	UCI-17776	-23.3	0.6	0.4460	0.0010	-554.0	1.0	6520	22	6520	20	7420 (7447)	7474 27
NIP 4–4.5	UCI-24215	-24.4	0.5	0.8745	0.0014	-125.5	1.4	1090	17	190	900	0 (976)	1952 976
NIP 10–10.5	UCI-21580	-25.5	0.4	0.7985	0.0024	-201.5	2.4	1800	26	1500	300	793 (1427)	2061 634
NIP 17–17.5	UCI-21579	-24.5	0.2	0.6309	0.0017	-369.1	1.7	3710	25	3410	300	2924 (3683)	444 759
NIP 31.5–32	UCI-17769	-20.5	0.6	0.3424	0.0009	-657.6	0.9	8700	25	8700	25	9552 (9628)	9703 76

Radiocarbon concentrations are given as fractions of the modern standard, $\delta^{14}\text{C}$, and conventional radiocarbon age, following the conventions of Stuiver and Polach (1977). Sample preparation backgrounds have been subtracted based on measurements of ^{14}C -free wood. $\delta^{13}\text{C}$ values were measured on prepared graphite using the AMS spectrometer. These can differ slightly (typically by 1–3‰) from those of the original material, if fractionation occurred during sample graphitisation or the AMS measurement. Uncorrected ages correspond to radiocarbon years, corrected ages were corrected for ^{13}C fractionation and calibrated ages were generated using the IntCal04 curve in Calib 5.0.1 (Stuiver and Reimer, 1993).

acids are reported in Table 2. In order to facilitate comparisons with previously published dates from across the region, which were neither systematically corrected for isotopic fractionation nor calibrated, we report dates in the text as such. However, we also include calibrated dates (cal. a BP; using Calib 5.0, Stuiver *et al.*, 2005) from our cores where appropriate.

In high-latitude environments, slow catchment processes (e.g. low plant decomposition and limited soil development) can sequester organic matter for prolonged periods of time before it becomes incorporated into the lake sediment archive (Wolfe *et al.*, 2004). This possible source of error must be considered when dating humic acid (HA) extracts, even if the fraction of autochthonous carbon is usually high in the humic fraction of sediments from oligotrophic lakes (Abbott and Stafford, 1996). The error associated with HA dates has been estimated to average 300–400 a (Olsson, 1986; Miller *et al.*, 1999, 2005) and appears to increase with time as soils develop in the catchment. In other words, as one moves further away in time from deglaciation, the discrepancy between the date obtained and the 'real' date of deposition will usually become larger due to a lag effect, or 'redeposition' (MacDonald *et al.*, 1991) caused by the deposition of carbon produced, stored and eroded from soils over time in the lake catchment.

The age reversal observed in the bottom section of the core from lac de l'Aéroport (Table 2) could be the result of differential weathering processes related to the input of old carbon from glacial debris. Lithology, LOI and biogenic silica all suggest a rapid accumulation rate at that epoch, therefore we opted to assign a global age of 8200–7500 cal. a BP (7200–6500 ^{14}C a BP) to the interval comprised between 50 and 23 cm in the AER core (Saulnier-Talbot *et al.*, 2009). Dates obtained from the Nipingngajulik sediments indicate a maximal age of about 9600 cal. a BP (8610 ^{14}C a BP). Our new dates are in accordance with previous studies in the region which suggest that deglaciation along the southern coast of Hudson Strait occurred between 10 000 and 7000 ^{14}C a BP (Gray, 2001, and citations therein). Based on the results of the dates obtained on humic acids, including the large possible errors associated with them, we deemed it inappropriate to create age–depth models for these cores. Therefore, we opted to keep the chronology to its most simple form here. This means that we cannot associate all depths of the cores with reliable ages, nor calculate precise sedimentation rates. Nonetheless, the dates that we have are closely associated with the depths in the cores

at which the assemblage switch takes place, and they allow us to estimate and compare their timing with other published studies on past environmental dynamics in this region.

Lac de l'Aéroport chironomid stratigraphy (Fig. 2)

In lac de l'Aéroport, the section encompassed between the core base at 50 cm and 23 cm corresponds to the period prior to ca. 6400 cal. a BP or 5750 ^{14}C a BP (22–22.5 cm was dated at 5750 ± 20 ^{14}C a BP, or 6350 ± 320 cal. a BP). The abundance of head capsules was at its peak during this initial phase of the lake's development (mean = 383 head capsules g^{-1} dry sediment, $n=14$). This pronounced abundance of head capsules is supported by the fact that this phase is also associated with a high sedimentation rate (see above). The DCA axis 1 scores show a pattern resembling that of chironomid abundance, with high gradient lengths between 50 and 24 cm, falling sharply thereafter. Indeed, following 24 cm, average chironomid abundance decreased to only 65 head capsules g^{-1} ($n=22$). During this initial period, the Tanytarsina (including *Micropsectra radialis*) were the dominant taxa (between 56% and 93% relative abundance). This group also includes species of the genera *Corynocera* and *Tanytarsus*; however, most head capsules lacked the necessary features (especially the mandibles) for more precise identification. *Micropsectra radialis* is widespread in northern regions of Canada, and is considered an indicator of cold temperatures and deep water (e.g. Barley *et al.*, 2006; Larocque *et al.*, 2006). The tribe Pentaneurini, likely consisting mostly of the genus *Telopelopia* (although Oliver and Roussel, 1983, stated that this genus was not known to occur in Canada), was the only other abundant group (up to 19% relative abundance) in this section of the core. These Tanypodinae disappeared at 24 cm and did not reappear. This pattern was also observed in Lake CF8, northeastern Baffin Island (Axford *et al.*, 2009). Most Pentaneurini are considered thermophilous and adapted to living in standing water and have been observed to decrease in numbers with increasing latitude or its climatological equivalent (Oliver and Dillon, 1997). It has also been suggested that the Subfamily Tanypodinae, which the Pentaneurini belong to, is not generally freeze-tolerant (Danks, 1971). However, some genera, such as *Arctopelopia*, are known from the Canadian Arctic region and others, such as

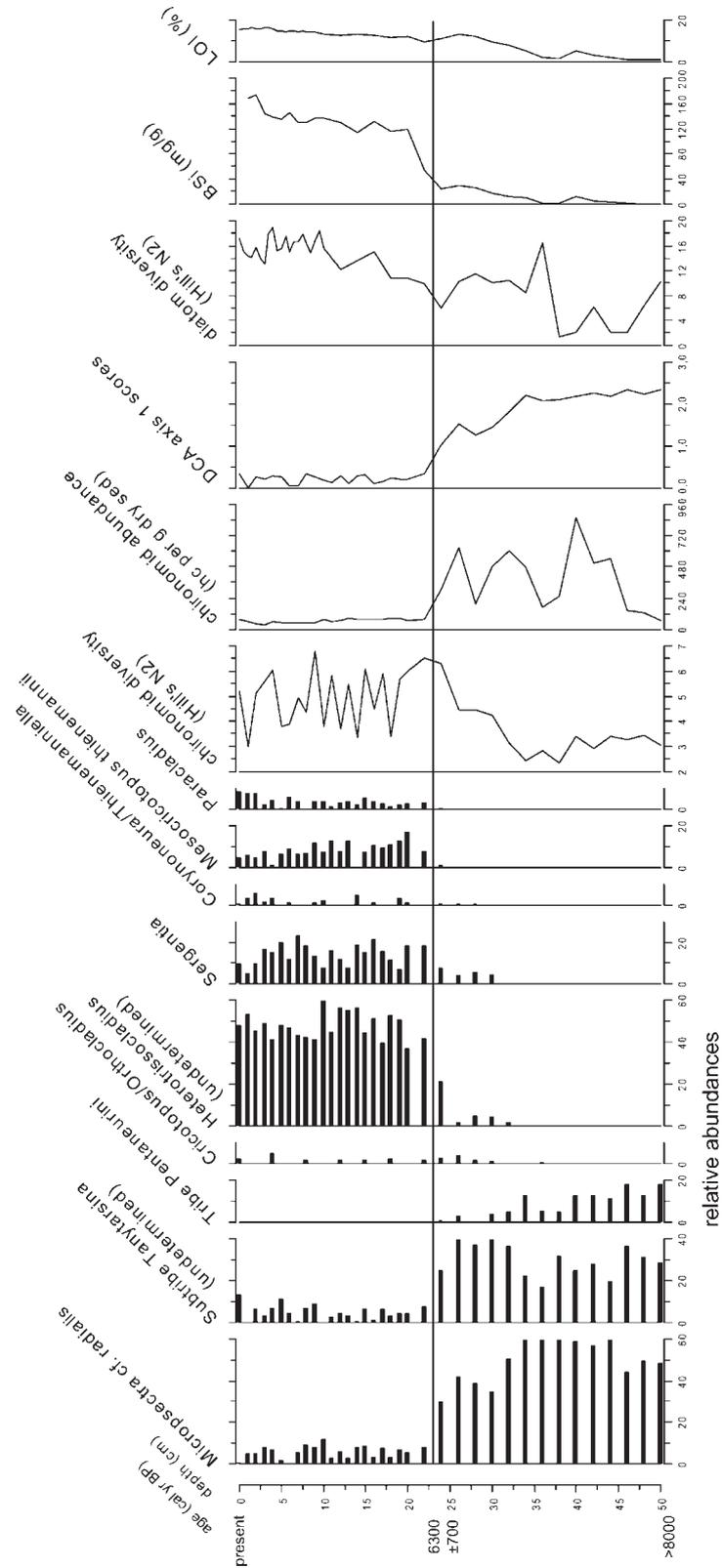


Figure 2 Lac de l'Aéroport sedimentary chironomid taxa expressed as percentages of the total number of head capsules counted, chironomid and diatom diversity expressed as Hill's N2, chironomid abundance, biogenic silica (BSi) concentration and % loss-on-ignition (LOI). Only taxa with a relative abundance of at least 5% in one sample are shown

Krenopelopia, *Larisa* and *Thienemannimyia*, occur in cool habitats and running water (Oliver and Roussel, 1983). Some Pentaneurini were also recorded from the surface sediments of many Labrador (Walker *et al.*, 1997) and northwestern Québec lakes (Larocque *et al.*, 2006), providing further support to the idea that some Pentaneurini taxa can thrive in cold climates.

Sergentia and *Heterotrissocladius* appeared in low relative abundances at 30 and 32 cm depth, respectively. The relative abundance of *Sergentia* increased up to 24% ($n = 22$) in the upper part of the core. *Sergentia* is usually considered to be a cold stenotherm and prefers deep oligotrophic lakes (e.g. Brooks and Birks, 2000; Porinchi *et al.*, 2008; Wiederholm, 1983). However, *Sergentia* showed little relationship to temperature in a northwestern North American training set (Barley *et al.*, 2006), but was highly correlated with deep lakes. Following 22 cm core depth, a major switch in chironomid faunal assemblages took place. This period is associated with an approximate age of 5750 ^{14}C a BP (between about 7000 and 5650 cal. a BP). *Heterotrissocladius*, including *H. grimshawi*, *H. subpilosus*, *H. marcidus* and *H. maeri*, became the dominant group and the assemblage diversified to include other cold-adapted Orthoclaadiinae such as *Paracladius*, *Parakiefferiella nigra* and *Mesocricotopus thienemanni*. In this interval, which extends to present times, the *Heterotrissocladius* group is dominant and comprises between 38% and 60% of the assemblage, whereas the relative abundance of the previously dominant Tanytarsina drops to an average of 12% ($n = 22$).

Lac de l'Aéroport siliceous sedimentary abundances and LOI

During the early postglacial development of lac de l'Aéroport, lake primary productivity, inferred from sedimentary biogenic silica (BSi) concentrations, was low (Fig. 2). Prior to 33 cm core depth, BSi and the relative proportion of LOI did not exceed 13 mg g^{-1} and 5%, respectively. Shortly following the time that the major switch in chironomid assemblage took place (see above), BSi concentrations, reflecting siliceous algal (diatom and chrysophyte) abundances, increased sharply from <55 to $>120 \text{ mg g}^{-1}$. LOI meanwhile had already reached values around 12%. It continued to increase slightly hereafter, reaching peak values around 17% at the core top. This overall relatively low organic matter content suggests a primarily minerogenic accumulation typical for arctic lakes with low productivity and sparse catchment vegetation.

Nipingngajulik chironomid stratigraphy (Fig. 3)

In Nipingngajulik, the lowermost 3 cm of the sediment core were devoid of any remains. Chironomids first appeared at 29 cm depth. During early lake ontogeny, the Subtribe Tanytarsina made up more than 90% of the assemblage. Tribe Pentaneurini was also present during this initial phase, but was not as abundant as in lac de l'Aéroport. During this interval, the abundance of sedimentary chironomid head capsules g^{-1} dry sediment increased from 86 head capsules at 29 cm, to a peak of 938 at 26 cm. Their abundance started to decrease at 25 cm, but remained high ($>600 \text{ g}^{-1}$ dry sediment) up to 21 cm, at which point the assemblage had started to diversify. During the following period, the abundance of chironomids decreased as their diversity increased. Subsequently, apart from two levels where the head capsule abundances reached 495 (15.5 cm) and 623 (13 cm) g^{-1} dry sediment, their numbers remained below 300 head capsules g^{-1} dry sediment (average of 233 head

capsules g^{-1} dry sediment; $n = 22$). The DCA axis 1 scores for this core also show a high correlation with chironomid abundances, with a low initial gradient length, followed by a sharp rise between 29 and 22 cm and finally a sharp decrease from 21 to 0 cm depth. On average over the postglacial period, chironomid remains have been about three times more abundant in Nipingngajulik than in lac de l'Aéroport.

Above 23 cm, the chironomid fauna diversified, as indicated by Hill's N2. At 22 cm, *Heterotrissocladius*, *Sergentia* and *Abiskomyia* appeared in low abundances. One half head capsule of *Mesocricotopus thienemanni* was found at 26 cm; however, from 21 cm onwards the species reappeared and increased in abundance with time. At 20 cm, *Chironomus* cf. *anthracinus* appeared in low relative abundances and remained present with abundances increasing up to 13% at present. *Chironomus* is often considered a temperate genus that is indicative of high lake productivity (Thienemann, 1954). The 'lumping' of *Chironomus* species in some northern North American studies unfortunately results in a wide distribution of the genus, rendering it less useful for palaeoecological reconstructions. In the eastern Canadian temperature inference model (Walker *et al.*, 1997) the genus was not found north of 57°N , but some species of *Chironomus* occur in high arctic ponds (Gajewski *et al.*, 2005; Walker *et al.*, 1997) and some are considered early colonisers of allochthonous organic sediments in well-oxygenated waters (Fjellheim *et al.*, 1993). Although the Tanytarsina remained dominant throughout the core, comprising between 31% and 99% of the assemblage, their dominance gradually decreased towards the core top. From 21 cm, *Heterotrissocladius* became an important part of the assemblage (16–35%), as did *Abiskomyia*, whose relative abundance gradually increased towards its maximum of 26% recorded at the core top. On nearby Baffin Island, *Abiskomyia* appeared only in late Holocene sediments; the brachypterous (short-winged) nature of the adults may explain their limited capacity for dispersal and therefore their late arrival at remote northern sites (Francis *et al.*, 2004; Gajewski *et al.*, 2005).

Nipingngajulik siliceous sedimentary abundances and LOI

During the early development of Nipingngajulik, siliceous algae were absent from the sedimentary record, in contrast to larval chironomids, which were more abundant at this time than at any other in the lake's history. Whereas chironomid head capsules became abundant from 29 cm onwards, no siliceous remains were found in levels below 24 cm. Diatom valves and chrysophyte cysts became more abundant from 18 cm onwards. This core depth has been dated to about 3700 ^{14}C a BP (between 4500 and 3000 cal. a BP). BSi values increased sharply at that time (from below 10 mg g^{-1} to over 100 mg g^{-1}) and followed an increasing trend up to recent times. Similar to observations in lac de l'Aéroport, Nipingngajulik sediments yielded low LOI throughout the core. The lowermost samples (below 28 cm) yielded $<6\%$ ($n = 7$), whereas when siliceous algae appeared in greater numbers between 24 and 18 cm core depth, LOI values increased to an average of 11% ($n = 13$). From 17.5 cm to the present day, LOI values increased further but remained at an average of only 14% ($n = 36$).

Discussion

Postglacial chironomid faunal succession was highly similar in both cores investigated. Initially, chironomid abundance was

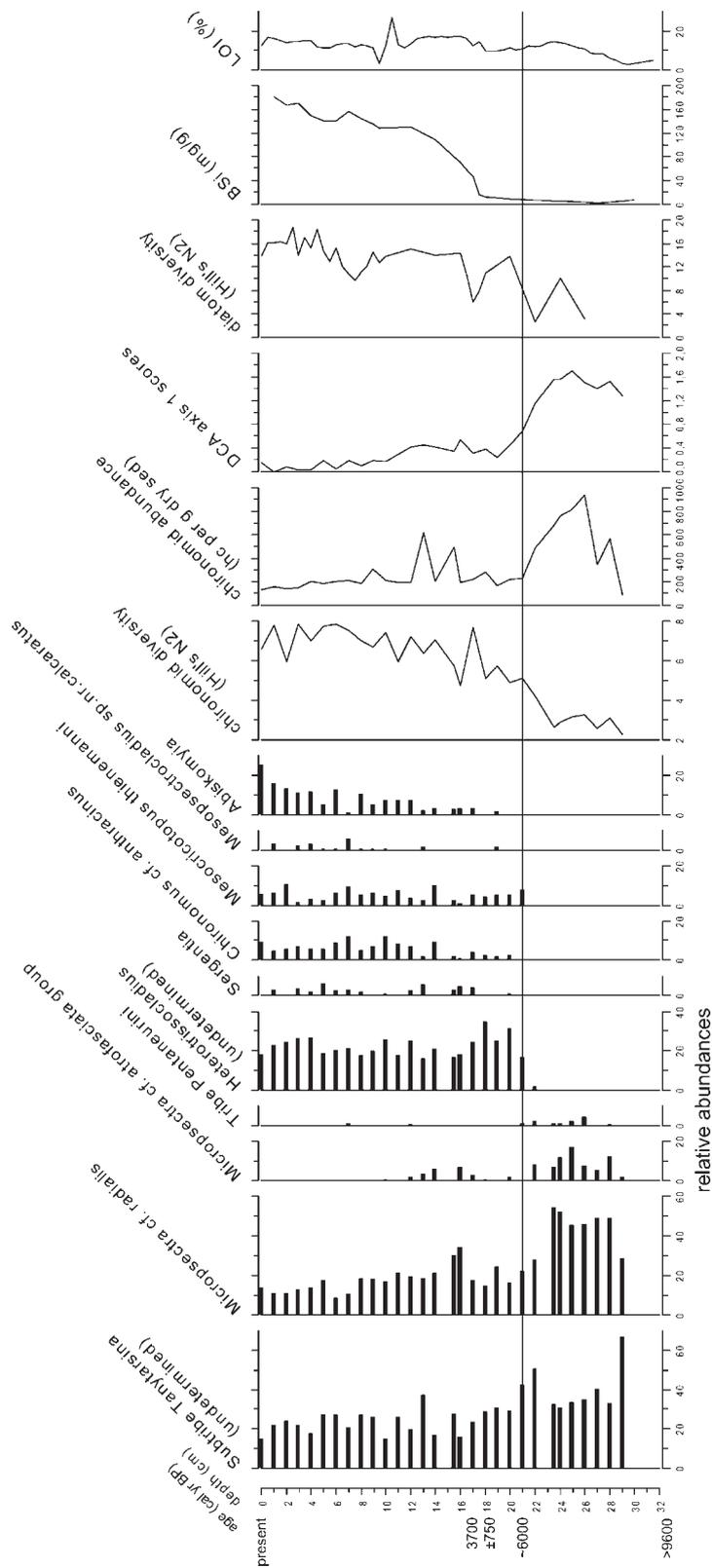


Figure 3 Nipingingajulik sedimentary chironomid taxa expressed as percentages of the total number of head capsules counted, chironomid and diatom diversity expressed as Hill's N₂, chironomid abundance, biogenic silica (BSI) concentration and % loss-on-ignition (LOI). Only taxa with a relative abundance of at least 5% in one sample are shown

high and the assemblages dominated by the subtribe Tanytarsina. Around 6 ka ago, there was a sharp decrease in chironomid numbers and the assemblages diversified and became dominated by species of Orthoclaadiinae. Many factors, such as dissolved oxygen concentrations, temperature, food availability, predation, competition and disturbance events, can affect chironomid population productivity and diversity. The marked differences in chironomid abundances between the early and late postglacial periods in our study lakes could potentially be linked to changes in water depth, possibly brought about by high rates of initial isostatic rebound. Within lentic systems, shallower areas may often support higher density and biomass of chironomids. Iwakuma (1987) found that overall chironomid production was negatively correlated with mean depth of water bodies. This would suggest shallower water depths in our two lake basins during the early postglacial period, when chironomid abundances were at their highest. However, in an analysis of environmental preferences of chironomids at various taxonomic levels in North American and European boreal lakes, no correlation was found between Tanytarsini and water depth (Mousavi, 2002). Nonetheless, both our cores show a switch in the mid Holocene to an assemblage which includes taxa associated with deep lakes, such as *Sergentia* and *Heterotrissocladius* (see, for example, Barley *et al.*, 2006; Larocque *et al.*, 2006).

Another possible explanation for the dominance of Tanytarsina and their high abundance during the early development of northernmost Ungava lakes could be linked to the differential productivity between the subfamilies. Tokeshi (1995) suggests that different subfamilies differ greatly in productivity, with the Chironominae (to which Tanytarsina belong) being the most productive and the Orthoclaadiinae having the lowest annual productivity of all the subfamilies. This would explain the high number of head capsules found during the period of sediment accumulation dominated by the Tanytarsina, and the higher overall postglacial chironomid productivity in Nipingngajulik (in which Tanytarsina have persisted at higher relative abundances throughout the postglacial) versus lac de l'Aéroport.

Another factor which could have had an important impact on chironomid abundance during the early postglacial period is food availability. In a latitudinal range of small Canadian lakes, Welch *et al.* (1988) found a positive correlation between chironomid abundance and plankton production. However, this relationship appears to be inverted in our two sediment cores, suggesting that perhaps the chironomids present in our lakes at that time were feeding on something other than algae, such as detrital matter. Chironomids can feed selectively on microbial communities, which are nutritiously more valuable than detrital matter (Tokeshi, 1995), or even on methanotrophs, as reflected by their isotopic signatures in some Scottish lakes (Grey, 2002).

The link between temperatures and the chironomid assemblages in our cores remains compelling, as chironomids have become a commonly used proxy for inferring past climate variations. At least two chironomid-based transfer functions are available for inferring past temperatures in the northern Québec region: (1) a model developed by Walker *et al.* (1997) to infer summer surface-water temperatures; and (2) a model developed by Larocque *et al.* (2006) to infer mean August air temperatures. However, the absence of modern analogues in these models for the chironomid assemblages found in the early postglacial period in our cores (Tanytarsina-dominated) prevented us from confidently applying them to our data. Recent studies have applied an extended version of the Walker *et al.* model (developed by Francis *et al.*, 2006) to similar early postglacial chironomid assemblages found in

nearby Baffin Island lake sediments (Francis *et al.*, 2006; Axford *et al.*, 2009). The Tanytarsina in this model are indicators of warmer temperatures, and therefore their results yielded the highest temperatures for the Holocene between about 10 000 and 8000 cal. a BP when this group was dominant. Their reconstructions are in good agreement with peak solar insolation for July at 65° N and high LOI values from the sediments indicating enhanced organic production.

The successional pattern of Tanytarsina dominance during the early postglacial, followed by a rise in diversity of the Orthoclaadiinae, is not rare in sedimentary chironomid studies of the eastern Canadian Arctic. In a lake on Southampton Island, in the Foxe Basin, southwest of Baffin Island, subfossils of the species *Corynocera oliveri*-type (a Tanytarsina) dominate the early postglacial sequence, dated at about 5500–4500 ¹⁴C BP (Rolland *et al.*, 2008). At this time, head capsule concentration was also at its peak and LOI values at their lowest. Similar to the aforementioned studies on Baffin Island, chironomid-inferred mean August air temperatures indicated their highest postglacial values (~10°C), which coincides well with peak Holocene warmth in the region (see below). Subtribe Tanytarsina was also the dominant group (around 60% relative abundance) in the early lacustrine phase (around 5 ka BP) of Lake Kachishayoot, a coastal basin that emerged from the postglacial Tyrell Sea near Kuujuaaraapik–Whapmagoostui, eastern Hudson Bay (K. Swadling, pers. comm.). The subtribe was also dominant throughout the postglacial sequence in Lake K2, near Kangiqsualujuaq (eastern Ungava Bay), but in notably higher relative abundances (around 60%) at the very beginning of lacustrine accumulation in the basin, before 6600 cal. a BP (Fallu *et al.*, 2005). In both these lakes, the high initial abundances of subtribe Tanytarsina were accompanied by low LOI, high sedimentation rates and high alkalinity. The timing of deglaciation in all these regions was highly asynchronous (Kaplan and Wolfe, 2006), but chironomid succession patterns were surprisingly similar.

In northernmost Ungava, the onset of deglaciation and the timing of the Holocene thermal maximum lags behind other regions of the northeastern Canadian Arctic (see, for example, Kaufman *et al.*, 2004; Kaplan and Wolfe, 2006). In this region, it appears the LIS, due to the stagnant nature of the ice front on the rugged coastline, remained a major component of the landscape long after deglaciation was initiated around 9 ka ago (Lauriol and Gray, 1987). Previous palaeoenvironmental reconstructions in this sector of the eastern Canadian Arctic using other proxies have consistently inferred a cool early postglacial period, followed by a warming trend from about 6 ka ago. Matthews (1967) suggested warmer temperatures around this time based on mollusc assemblage remains found on the shores of Sugluk (Salluit) Fjord. Palynological analyses of lake sediments from Diana Bay, near Quaqtq (northeastern coast of Ungava Peninsula) documented the passage from a herb to a shrub tundra sometime after 6000 ¹⁴C a BP (Richard, 1981). Similar successional schemes based on pollen analyses also emerged from other regions of the eastern Canadian Arctic (Williams *et al.*, 1995), such as southern Baffin Island and northern Labrador, and also from western Greenland (Mode, 1996). Multi-proxy palaeoenvironmental reconstructions from a small lake (K2) near the eastern Ungava Bay coast (Fallu *et al.*, 2005) indicated a cold early postglacial, followed by a warming trend from about 6400 cal. a BP. Marine proxies also attest that the ocean waters of the eastern Canadian Arctic were cold in the early postglacial period and warmed around 6000 ¹⁴C a BP (Williams *et al.*, 1995). Palaeolimnological evidence (from palaeoproductivity proxies such as BSi and LOI) from southern Greenland points to peak Holocene warmth around 6000 cal. a BP at the outer margin of the northeastern Canadian fringe

(Kaplan *et al.*, 2002). The bulk of the literature for this region therefore points to cold temperatures during the early postglacial, followed by warming around 6 ka ago. This evidence leads us to believe that the dominance of Tanytarsina, at least in our study lakes, was perhaps more weakly linked to temperature than suggested by the studies on Baffin and Southampton Islands, where deglaciation coincided with peak summer solar insolation and the Holocene thermal maximum, respectively.

Based on the above observations, we suggest that some attention should now be focused on ways of resolving the question of what environmental variables drive colonisation patterns of chironomids in early postglacial environments. With this in mind, laboratory experiments could be conducted to test the preferences and tolerances of the taxa commonly found in early Holocene sediments to conditions such as high alkalinity, high turbidity and low food availability, which are typical of early postglacial lakes. Receding glaciers are becoming more common throughout the eastern Canadian Arctic due to climate warming and offer an opportunity to study how chironomids colonise the newly deglaciated terrain. Such studies will increase our understanding of postglacial succession in high-latitude environments. Additionally, the use of other, non-taxonomically dependent proxies, such as stable isotopes of biogenic silica and chitin, could provide complementary independent temperature inferences for the early postglacial, against which to test chironomid assemblage-based inferences. These reconstructions could also potentially improve our understanding of early postglacial climate dynamics in the North Atlantic region.

The Tanytarsina can be considered a eurythermal group. For example, it was present in all the lakes from the calibration set developed for eastern Canada (Walker *et al.*, 1997), from latitude 45° to 75° North, yet it was well represented in the High Arctic sites of this model, where it made up between 20% and 60% of the modern assemblages. Although more precise autecological and environmental information could be gained by employing a higher taxonomic resolution, missing features of Tanytarsina head capsules in our cores generally did not allow for reliable identification to genus or species level. More rearing of chironomids in the laboratory would help improve the head capsule-based taxonomy and our knowledge of their autecology, thus moving this science forward.

Conclusions

The radiocarbon dates obtained from the bottom of our sediment cores confirm earlier findings that the coastal landscape was ice-free by 8000 cal. a BP (7200 ¹⁴C BP) in the vicinity of Salluit, but that near Kangiqsujuq the ice had started to retreat as early as 9600 cal. a BP (8700 ¹⁴C a BP). The palaeolimnological data presented in this study provide evidence for early postglacial lake dynamics that were similar at two locations along the southern shore of Hudson Strait, reflecting the biogeographical effects of the retreat patterns of the LIS in northern Québec. The sedimentary chironomid assemblages and BSi concentrations suggest that a major environmental disturbance, perhaps linked to the final disappearance of the LIS, occurred in the region around 6 ka ago. This is consistent with earlier findings that suggested this period as one of major change around the eastern Canadian Arctic.

This study also highlights the similar successional pattern of postglacial chironomid recolonisation in the northeastern

Canadian Arctic, characterised by an early arrival and dominance of taxa belonging to the subtribe Tanytarsina, followed by diversification and a shift to a dominance of Orthoclaadiinae in the subsequent millennia. The presence of this pattern in lakes located in asynchronously deglaciated regions leads us to believe that environmental factors other than temperature might have driven the ability of the Tanytarsina to become established in recently deglaciated landscapes and their aquatic ecosystems. The subtribe Tanytarsina is a successful group, often occurring in high numbers and accounting for high proportions of the chironomid fauna in lakes spanning extensive latitudinal gradients (e.g. Walker *et al.*, 1997). Based on the new findings presented here, we suggest that some Tanytarsina might have a competitive advantage in lakes with low primary productivity and possibly high alkalinity and turbidity, conditions typical of early postglacial lake development.

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