



Postglacial environmental history of western Victoria Island, Canadian Arctic

Marie-Claude Fortin*, Konrad Gajewski

Laboratory for Paleoclimatology and Climatology (LPC), Ottawa-Carleton Institute for Biology, University of Ottawa, Ottawa, ON K1N 6N5, Canada

ARTICLE INFO

Article history:

Received 6 June 2009

Received in revised form

4 May 2010

Accepted 6 May 2010

ABSTRACT

Changes in chironomid species assemblages and community dynamics at Lake KR02, western Victoria Island were analysed to produce a record of environmental change over the Holocene for the western Arctic. Past air temperatures were inferred from the chironomid record using transfer function and modern analogue techniques, and past lake water pH was reconstructed using sediment carbonate and biogenic silica content. The early-Holocene (10.2–6.5 ka) was a warm period of high aquatic and terrestrial production. A further change in environmental conditions occurred at 4 ka and lasted for the next two millennia. Conditions warmed abruptly at 1.6 ka, and rapidly cooled at ~1.0 ka. A warming then started at 0.14 ka and continued through to recent times, although temperatures still remained cooler than those experienced prior to 6.5 ka. The climatic changes over the Holocene as recorded at Lake KR02 are consistent with those inferred from independent records from other sites on Victoria Island and across the Arctic.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Instrumental records document a warming during the past century at a number of sites across the Arctic (ACIA, 2005). Interpretations of paleolimnological data, extracted from Arctic lake sediment cores, also show changes in species composition and production, and these have been interpreted as a result of this recent increase in temperature (e.g., LeBlanc et al., 2004; Smol et al., 2005; Podrisky and Gajewski, 2007). Paleoenvironmental proxy records extend back before the instrumental record and indicate that the climate has been continually changing over the last 10,000 years in the Canadian North, as elsewhere (e.g., Gajewski and Atkinson, 2003). Questions remain, however, about the timing and magnitude of Holocene climate variability in the Arctic.

Lake sediments archive past environmental conditions through the preservation, within the sediment matrix, of fossils of organisms and material that were present in the lake or on the surrounding landscape. From these proxy climate records, past environmental conditions can be inferred. These archives are a major source of information about past climates, although there are few such records from the Canadian Arctic that span the entire postglacial period (Gajewski and Atkinson, 2003). However, interpretation of these records is not necessarily straightforward, and

a consistent and quantitative interpretation of the postglacial climates of the Canadian Arctic region is still lacking.

This study will examine the chironomid fossil record for Lake KR02 located on western Victoria Island. A high-resolution diatom study was previously conducted on this core (Podrisky and Gajewski, 2007) and Peros and Gajewski (2008) provided a detailed pollen record. There exist, however, certain discrepancies between the interpretations of these records. In particular, periods of low diatom production, typically interpreted as indicating cold temperatures, were identified when the pollen record suggested warm conditions. Although changes in pollen influx showed large changes from the early- to late-Holocene, estimates of past temperature showed less variability.

The purpose of this study was to determine, based on the chironomid record, what climatic conditions existed in the western Victoria Island region over the Holocene. We compare the chironomid record to the pollen and diatom records, allowing us to better understand the behaviour of these two groups of organisms and pollen through time and account for the timing and extent of both changes in overall production of the lake ecosystem and in the biodiversity of the species assemblages. Finally, the climatic record for western Victoria Island will be compared to other Holocene records from the central Canadian Arctic. By comparing the various proxy climate records from western Victoria Island among themselves, as well as to other records from the region and then to sites from across the Arctic we will be better able to determine the geographical extent and timing of the climatic changes occurring throughout the Holocene.

* Corresponding author. Tel.: +1 613 562 5800x1327; fax: +1 613 562 5145.
E-mail address: mfort011@uottawa.ca (M.-C. Fortin).

2. Study area

Lake KR02 is located in the Kuujjua River region of northwestern Victoria Island in the Northwest Territories of the Canadian Arctic (71.34°N, 113.78°W, 299MASL; Fig. 1). The lake has a surface area of 7900 m² and a maximum depth of 6.2 m at the coring location. Lake KR02 is oligotrophic (TP = 0.226 µmol L⁻¹) and circumneutral (pH = 7.3).

The lake is underlain by clastic and carbonate sediments as well as basalts from the Kilian Group of the Shaler Formations and the Natkusiak Formation (Frisch and Trettin, 1991). It is surrounded by prostrate shrub tundra (CAVM team, 2003). January and July air temperature normals (1971–2000) for the closest weather station (Ulukhaktok/Holman) are −28.6 °C and 9.2 °C respectively (Meteorological Survey of Canada, 2006). Further information regarding the environmental characteristics of Lake KR02 can be found in Bouchard et al. (2004), Podritske and Gajewski (2007) and Peros and Gajewski (2008).

3. Field methods

A sediment core measuring 411 cm was taken from the central location of Lake KR02 using a 5-cm diameter Livingston piston corer. The top 20 cm of the core was extruded at 0.5 cm intervals in the field to preserve the sediment–water interface. The remaining sediment was wrapped in layers of plastic wrap and foil and stored at 4 °C. Lake water was collected from 1.5 m below the ice for water chemical analysis. Complete water chemistry results for Lake KR02 are available in Bouchard et al. (2004).

4. Laboratory analysis

The core chronology was established using 9 AMS radiocarbon dates and ²¹⁰Pb dating, which provided an age estimation for each

of the top 21 cm (Table 1 and Table 2). The resulting age–depth model, based on a linear interpolation after calibration is described in Peros and Gajewski (2008) (Fig. 2). Calibrated ages are reported in this manuscript as ka (1000 years before present), with a base of AD 2000. The basal date of ~10.5 ka of the sediment core is extrapolated from the age–depth model as the oldest radiocarbon date obtained was ~9.8 ka old. Dyke (2004) proposes that the Kuujjua Region was likely deglaciated by ~12 ka.

Sediment analyses, including sediment organic, carbonate and biogenic silica content estimations and magnetic susceptibility (MS) measurements followed standard protocols and are outlined in Podritske and Gajewski (2007). Sediment organic, carbonate and biogenic silica content that were previously reported as dry weight % were also converted to dry weight accumulation rates (g cm⁻² yr⁻¹).

Chironomid head capsules and mandibles were extracted and identified for a total of 116 levels following methods in Walker (2001). Sediment for chironomid analysis was sampled every 0.5 cm for the top 20 cm of the core and at 1 to 5 cm intervals for the remaining portion of the core. Samples of between 2 and 7 cm³ of wet sediment, taken over 0.5 cm wide thicknesses of sediment for the top 20 cm and 1 cm wide thicknesses for the rest of the core, were soaked in warm 10% KOH. The deflocculated material was sieved through 90 µm-mesh using deionised water. Midge head capsules and mandibles were then picked from a Bogorov sorting tray using 20–40× magnification, and mounted on slides using Entellan™. To account for differences in sedimentation rate chironomid accumulation rates (HC cm⁻² yr⁻¹) are also presented.

Chironomid identifications were made using taxonomic keys provided by Walker (1988, 2000), Barley (2004), Heiri et al. (2004), Larocque and Rolland (2006) and Brooks et al. (2007). *Tanytarsus* spp., *Micropsectra* spp. and *Paratanytarsus* spp. were identified using Heiri et al.'s (2004) identification key. *Heterotrissocladius* spp. identifications followed Larocque and Rolland (2006) and

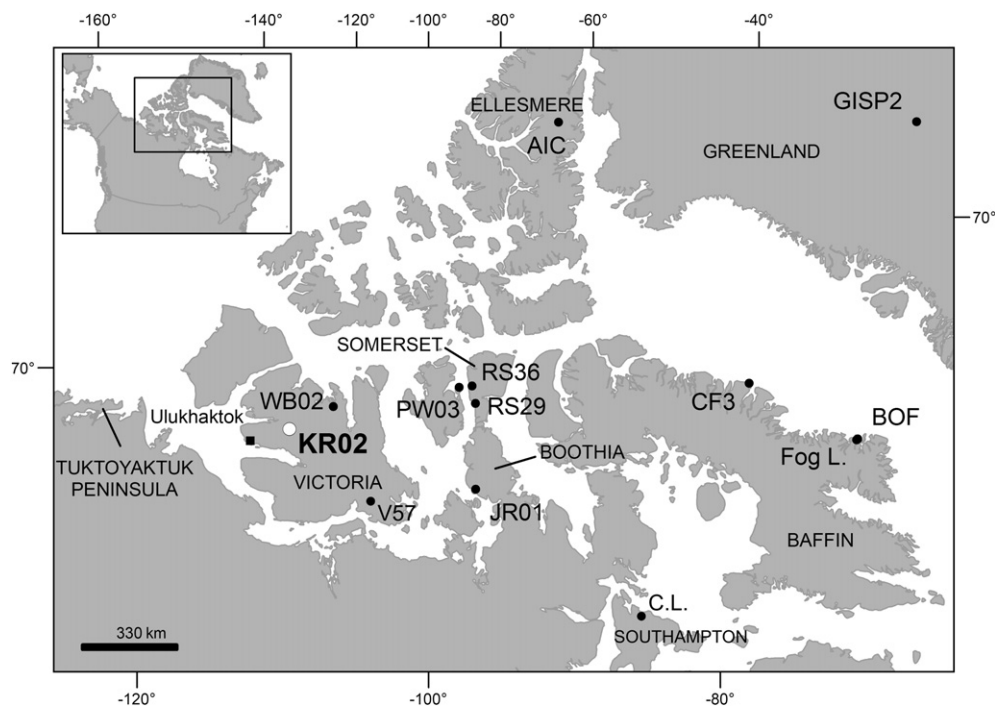


Fig. 1. Map indicating location of Lake KR02 in the Northwest Territories. Lakes and ice cores referred to in the text are indicated: AIC Agassiz Ice Core (Fisher et al., 1995), GISP2 Ice Core (Alley, 2000), Lake CF3 (Briner et al., 2006), Lake PW03 (Finkelstein and Gajewski, 2007), Lake WB02 (Fortin and Gajewski, 2009b), Lakes RS29 and RS36 (Gajewski, 1995), Lake JR01 (diatoms: Leblanc et al., 2004; pollen: Zabenskie and Gajewski, 2007) and Fog and “Brother of Fog” Lake (B.O.F.) (Wolfe, 2003; Francis et al., 2006), “Caribou” Lake (C.L.) (Rolland et al., 2008) and Lake V57 (Porinchu et al., 2009b).

Table 1

Radiocarbon dates, calibrated ages (cal BP, with base 1950 AD), and calibrated ages ka (base of 2000 AD). The date at depth of 404–407 cm was not included in the age–depth curve.

| Lab code (Beta) | Depth (cm) | Conventional radiocarbon age yr BP | Calibrated 2σ range age yr BP | Median calibrated age yr BP | Age ka (before 2000 AD) | Material dated |
|-----------------|------------|------------------------------------|--------------------------------------|-----------------------------|-------------------------|----------------|
| Beta-199874 | 37.5–39.5 | 890 \pm 40 | 710–920 | 815 | 0.865 | Bulk sediment |
| Beta-199875 | 70–73 | 1680 \pm 50 | 1500–1710 | 1605 | 1.655 | Macrofossils |
| Beta-199877 | 208–209 | 3500 \pm 40 | 3670–3870 | 3770 | 3.820 | Macrofossils |
| Beta-206009 | 241–243 | 4270 \pm 40 | 4820–4870 | 4845 | 4.895 | Bulk sediment |
| Beta-199878 | 291–293 | 5760 \pm 50 | 6430–6670 | 6550 | 6.600 | Bulk sediment |
| Beta-206010 | 314–317 | 6150 \pm 50 | 6890–7200 | 7045 | 7.095 | Macrofossils |
| Beta-206011 | 333–335 | 7050 \pm 50 | 7760–7960 | 7860 | 7.910 | Macrofossils |
| Beta-213872 | 349–351 | 8590 \pm 40 | 9520–9570 | 9545 | 9.595 | Macrofossils |
| Beta-199879 | 362–364 | 8730 \pm 60 | 9550–9920 | 9735 | 9.785 | Macrofossils |
| Beta-206012 | 404–407 | 18950 \pm 170 | | Rejected | | Bulk sediment |

Zalutschia spB is according to Barley et al. (2006). Oliver and Roussel (1983) and Wiederholm (1983) reference manuals were also consulted. Where possible, head capsules were identified to the species group or morphotype and these specific identifications were subsequently selectively combined to facilitate analysis. *Micropectra* spp. includes both *Micropectra radialis*-type and *Micropectra insignilobus*-type, although *M. radialis*-type is only present in 4 levels and only accounts for less than 1% of all the specimens in the *Micropectra* spp. group. Similarly, *Paratanytarsus* spp. includes *Paratanytarsus austriacus*-type, *Paratanytarsus penicillatus*-type and indeterminate *Paratanytarsus austriacus/penicillatus* – type. *Tanytarsus* spp. includes *Tanytarsus lugens*-type, *Tanytarsus mendax*-type and indeterminate *Tanytarsus lugens/mendax* spp. All morphotypes and intermediary forms of *Cricotopus* and *Orthocladius*-type species have been combined into *Cricotopus/Orthocladius* spp. *Cricotopus cylindraceus*-type, *Cricotopus (Isocladius) intersectus*-type, *Cricotopus (Isocladius) laricomalis*-type and *Cricotopus (Isocladius) sylvestris*-type, as identified after Brooks et al. (2007), were found at various levels throughout the core. As the proportion of indeterminate *Cricotopus/Orthocladius* remained greater than the identifiable ones, all *Cricotopus/Orthocladius* morphotypes were combined into *Cricotopus/Orthocladius* spp. *Heterotrissocladius maeaeeri*-type includes four morphotypes of this species. *H. maeaeeri*-type1-dark has no accessory tooth on the median tooth and the head capsule is dark from the bottom of the mentum to the post occipital plate. *H. maeaeeri*-type1-light also has no accessory tooth on the median tooth but is only slightly pigmented just below the mentum. *H. maeaeeri*-type2-dark and *H. maeaeeri*-type2-light are similar to type1 forms but type-2 specimens have an accessory

tooth on either side of the median tooth. The less pigmented head capsules may be younger instars of the darker ones.

Information regarding chironomid temperature optima and particular taxon environmental preferences was taken primarily from Barley (2004), Gajewski et al. (2005), Francis et al. (2006), Larocque et al. (2006) and Porinchu et al. (2009a). Further qualitative information regarding ecological preferences was taken from Brooks et al. (2007).

In the following, all characteristics relating to a taxon's optimal temperatures and ecological preferences are relative to the other taxa found in the core. However, based on the available North American chironomid training sets there are conflicting results with respect to the optimal air temperatures of some of the important taxa in core KR02. This is due in part to the particular geographic sample set used by various authors to define temperature optima and tolerance, but also to differences in taxonomic resolution in the existing modern Arctic chironomid data (Gajewski et al., 2005; Barley et al., 2006; Francis et al., 2006; Larocque et al., 2006; Porinchu et al., 2009a). When considering taxa from the subtribe Tanytarsina, it is difficult to resolve the temperature optima of the different taxa within this subtribe. For example, *Micropectra* spp. is identified as a cold-tolerant genus by Barley

Table 2

^{210}Pb dates (AD) and age (ka) for the KR02 sediment core. Years and ages are those of the bottom of each sample interval and were determined using a CRS model estimate.

| Depth (cm) | Year AD | Age ka (before 2000) |
|------------|---------|----------------------|
| 2.0–3.0 | 1995 | 0.005 |
| 3.0–4.0 | 1993 | 0.007 |
| 4.0–5.0 | 1990 | 0.010 |
| 5.0–6.0 | 1985 | 0.015 |
| 6.0–7.0 | 1980 | 0.020 |
| 7.0–8.0 | 1976 | 0.024 |
| 8.0–9.0 | 1972 | 0.028 |
| 9.0–10.0 | 1957 | 0.043 |
| 12.0–13.0 | 1934 | 0.066 |
| 14.0–15.0 | 1920 | 0.080 |
| 16.0–17.0 | 1901 | 0.099 |
| 18.0–19.0 | 1873 | 0.127 |
| 20.0–21.0 | 1837 | 0.163 |

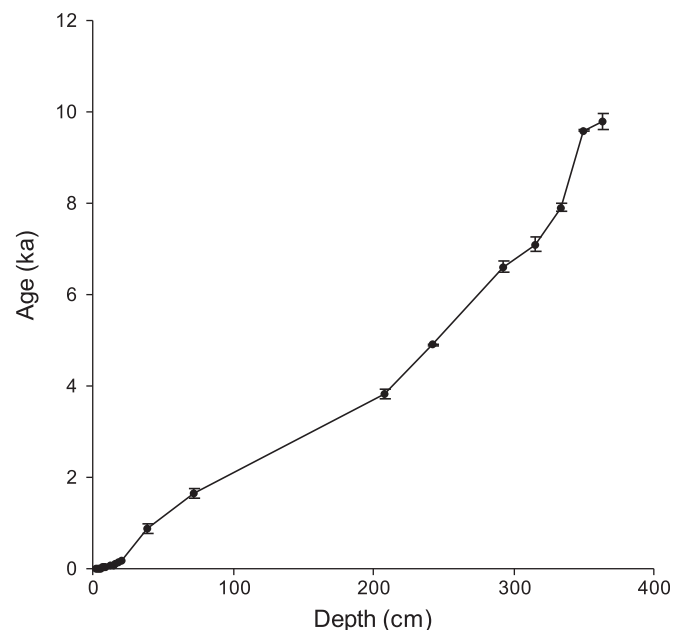


Fig. 2. Age–depth curve for Lake KR02 based on ^{14}C and ^{210}Pb dating. All ages reported in ka with base AD 2000. Error bars represent 95% age confidence intervals.

et al. (2006) and Brooks et al. (2007), but is considered tolerant of intermediate temperatures in Porinchu et al. (2009a). Furthermore, Larocque et al. (2006) separate *Micropsectra* head capsules to morphotype and identify *M. insignilobus*-type as also being tolerant of intermediate condition and *M. radialis*-type as preferring colder conditions. Brooks et al. (2007) also identify *M. insignilobus*-type as preferring warmer conditions than *M. radialis*-type. *Cricotopus/Orthocladius* is another complex group whose optimal temperatures can range from cold tolerant in Porinchu et al. (2009a), to moderate in Francis et al. (2006), to moderate-warm in Barley et al. (2006). A similar problem occurs with *Corynocera oliveri*, which is described as a warm-tolerant taxon by Barley et al. (2006), but appears to indicate more moderate to cold conditions (Porinchu et al., 2009a; Larocque et al., 2006). Gajewski et al. (2005) had previously determined that the distribution of *C. oliveri* in the Arctic had no significant relation to temperature and it was generally found in lakes with higher dissolved organic carbon (DOC) concentrations. *Sergentia*, which is identified as preferring cold conditions in the Porinchu et al. (2009a), Larocque et al. (2006) and Francis et al. (2006) training sets, indicates cold to moderate air temperatures according to Barley et al. (2006). We have taken into account these differences in our interpretation.

5. Data analysis

A principal component analysis (PCA) was performed using only the chironomid fossil data (relative abundances %). Only levels with more than 30 head capsules and taxa with a mean relative abundance >1% averaged overall levels were included. Using a lower minimum total head capsule for inclusion than the often-used 50 HC (Heiri and Lotter, 2001; Quinlan and Smol, 2001; Larocque, 2001) is necessary in very unproductive Arctic ecosystems in order to retain any information regarding the most unproductive periods in the history of these Arctic lakes (Fortin and Gajewski, 2009b). A total of 9 levels out of the 92 retained had head capsule counts between 30 and 40.

Using data from Barley et al. (2006), mean July air temperatures were reconstructed from the KR02 midge fossil data. Chironomid taxonomy from the KR02 core was harmonized with that of Barley et al. (2006) prior to performing the reconstruction. All *Tanytarsus* and *Paratanytarsus* taxa from the KR02 core, as well as all remaining taxa from the subtribe Tanytarsina that could not be further identified were combined as Tanytarsina-other. All *Heterotrissocladius* taxa were also combined as *Heterotrissocladius* spp. Environmental reconstruction using both a weighted average partial least squares transfer function (WAPLS with three components and 1000 bootstrap cycle cross-validated r^2_{boot} of 0.818 and RMSEP of 1.46 °C) and a modern analogue technique (MAT, squared chord distance dissimilarity coefficient, retaining 5 analogues) were performed. The WAPLS model provided the most robust reconstructions (best performance statistics; Barley et al., 2006), and the MAT was also used in order to show the geographical location of the closest modern analogues to the downcore fossil data and assess the appropriateness of the modern data as analogues of the fossil assemblages. All taxa found in the core were present in the training set. Only levels with 30 head capsules or more were included in the reconstruction.

Based on sediment carbonate and BSi weight % from the sediment core, a pH reconstruction was constructed using a model derived by Fortin and Gajewski (2009a) ($r = 0.51$, $p = 1 \times 10^{-4}$).

6. Results

Organic weight% and accumulation rate (AR) profiles both showed a long-term increase of organic matter through time (Fig. 3). Sediment BSi weight% and AR were highest between 10.2–9.5 ka and 7.2–6.5 ka

with two increases starting at 4.0 ka and again around 0.2 ka until the recent sediment. BSi content is an index of diatom and chrysophyte production. These periods of high BSi weight% and AR correspond to slightly elevated values of organic accumulation rates. These peaks occurred every ~3000 years (Fig. 3). The abrupt nature of the changes of the organic AR at various points in the Holocene is due to the linear interpolation used to create the age–depth curve; using a different age–depth model would smooth the abrupt transitions in organic AR, however the overall pattern would remain the same. Carbonate percentages are high between 6 and 4.5 ka and magnetic susceptibility was high at the bottom of the core, decreased at around 10 ka and remained low to the present (Fig. 3).

6.1. Chironomids

6.1.1. Concentration and accumulation rate

Chironomid head capsule (HC) concentrations ranged from 1 to 116 HC cm⁻³ (Fig. 3). Both chironomid concentrations and chironomid accumulation rates had similar overall trends through the Holocene. Three of the highest peaks in chironomid production occurred during the early- to mid-Holocene, between 10.2–9.5 ka, 8.3–7.5 and 7.0–6.5 ka. The peaks starting at 10.2 and 7.0 ka correspond to relatively high values of organic AR. Between 6.5 and 4.0 ka, HC concentrations were the lowest of the core. Concentrations were slightly higher between 4.0 ka and 1.0 ka. A large peak in chironomid concentration and AR occurring at 1.6 ka is due to the very high production of *C. oliveri*-type at that one level in the core. After 1.0 ka chironomid production decreased, and remained low until 0.14 ka when chironomid AR again increased rapidly.

6.1.2. Chironomid composition

A total of 40 taxa were recovered from the KR02 sediment core (Fig. 4). Taxa found in the KR02 core were similar to those found in a sediment core from Northern Victoria Island (LakeWB02, Fortin and Gajewski, 2009b) and are typical of those found in cold, nutrient-limited Arctic lakes.

Before 9.9 ka, both cold- and warm-tolerant taxa were present in the sediment. Taxa from the subtribe Tanytarsina, including Tanytarsina-other and *Micropsectra* spp. (specifically *M. insignilobus*-type) (Francis et al., 2006; Larocque et al., 2006; Porinchu et al., 2009a) were the most abundant individuals during this period. All the dominant taxa found somewhere in the core were present during this time, except for *Abiskomyia* and *Pseudodiamesa*, both of which are cold-tolerant taxa (Barley et al., 2006; Francis et al., 2006; Brooks et al., 2007; Porinchu et al., 2009a) and warmer water *Psectrocladius* (*Psectrocladius*)-type (Barley et al., 2006; Francis et al., 2006; Brooks et al., 2007; Porinchu et al., 2009a).

From 9.9 to 7.5 ka, cold-tolerant *Paracladius* and *Sergentia*, which is either cold tolerant or is most abundant in intermediate conditions, were found in low abundance (Barley et al., 2006; Francis et al., 2006; Brooks et al., 2007; Porinchu et al., 2009a). The chironomid assemblages were dominated by the warm and intermediate-tolerant taxa of the subtribe Tanytarsina (Tanytarsina-other, *Micropsectra* spp. *Paratanytarsus* spp. and *Tanytarsus* spp.) which made up on average 50% of the total assemblage. *Paratanytarsus* spp. was present throughout the record, but reached highest abundances in the early-Holocene. *C. oliveri*-type was more abundant in this time period than at any other time in Holocene, with the exception of one large peak at 1.6 ka. *Chironomus anthracinus*-type, which is a taxon that prefers moderate to warm temperatures (Barley et al., 2006; Francis et al., 2006; Brooks et al., 2007; Porinchu et al., 2009a), also disappeared from the assemblage at this time and only returned in low abundance at 8.4 ka. Neither *Abiskomyia* nor *Pseudodiamesa*, two taxa with very cold mean July air and water temperature optima, were part of the

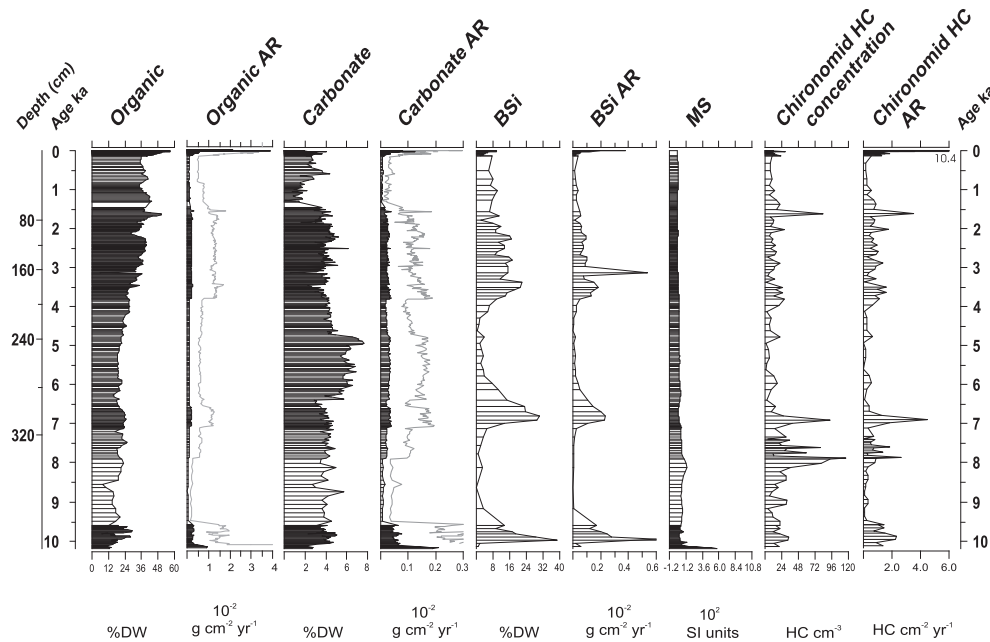


Fig. 3. Biogeochemical sediment parameters of Lake KR02. All sediment proxies excluding magnetic susceptibility (MS) are reported in weight % or concentration and as accumulation rates (AR). Organic (LOI550) and carbonate (LOI950) plots each include a 5× exaggeration line (grey). The high values in the upper sediment of the chironomid head capsule (HC) AR were truncated and the value at 0.018 ka is indicated directly on plot. Ages are ka (1000 years) before AD 2000.

assemblage during this period. However, other taxa tolerant of cold to moderate temperatures, such as *Parakiefferiella nigra*-type (Barley et al., 2006; Brooks et al., 2007) and *Heterotrissocladius* spp., were more abundant during this time than at any other point in the core (Barley, 2004; Gajewski et al., 2005; Francis et al., 2006; Larocque et al., 2006). Rarer taxa such as warm-tolerant *Procladius*-type (Gajewski et al., 2005; Barley et al., 2006; Francis et al., 2006; Brooks et al., 2007; Porinchu et al., 2009a) and *Psectrocladius* (*Psectrocladius*)-type were also present in the core.

A change in chironomid composition occurred from ~7.5 to 6.5 ka, when warm-tolerant taxa were replaced by cold-water taxa. Several taxa, including *Micropsectra* spp. and *Tanytarsina*-other decreased in abundance as *Paracladius* and *Sergentia* increased. *C. anthracinus*-type, which had been absent from the sediment between 9.9 and 8.5 ka, became more abundant and peaked at ~7.1 ka. This taxon has been found in sediment assemblages after large disturbances, even if under sub-optimal conditions (Brooks et al., 2007).

From 6.5 to ~4.0 ka, the warm-tolerant taxa all but disappeared from the assemblages, being initially replaced by the cold-water taxon *Paracladius*, the cold- to moderate-tolerant *Sergentia* and moderate- to warm-tolerant *Zalutschia* spB (Barley et al., 2006; Francis et al., 2006; Porinchu et al., 2009a). These taxa dominated until ~6.0 ka when *Abiskomyia* entered the assemblage, in low relative abundance for the first 1000 years, but then dominating from 4.8 to 4.0 ka with relative abundance as high as 60%. At 5.7 ka, *Cricotopus/Orthocladius* spp. was abundant; it subsequently decreased until 3.3 ka. *Cricotopus/Orthocladius* spp. appear to be cold to moderate temperature tolerant (Barley et al., 2006; Francis et al., 2006; Porinchu et al., 2009a), however this group integrates a large number of presently undifferentiated taxa whose respective temperature optima may be different. *C. anthracinus*-type abruptly decreased in relative abundance after 7.1 ka but remained on average 10% of the assemblage until ~0.7 ka.

After 4.0 ka, the relative abundance of *Abiskomyia* decreased and the cold-tolerant taxa that were present in the core prior to the dominance of *Abiskomyia* once again increased in abundance.

Paracladius became the most abundant taxon in the assemblage for the remainder of the Holocene. *Sergentia*-type was also an important taxon at this time. Although in lesser relative abundance, *Pseudodiamesa* reached maximum values during the time period from 4 ka to 1.6 ka. *Abiskomyia* reappeared in higher abundance between 2.0 and 1.8 ka, as did *Pseudodiamesa*, replacing *Paracladius*.

After 1.6 ka the warm-tolerant taxa present in the assemblage during the early-Holocene again increased in abundance, especially *C. oliveri*-type, which at 1.6 ka represented 55% of the assemblage. Taxa from the subtribe Tanytarsina became more abundant, as did the rarer warm-tolerant *Psectrocladius* (*Psectrocladius*)-type and *Procladius*. Colder-tolerant taxa such as *Abiskomyia*, *Pseudodiamesa* and *Paracladius* decreased in abundance or simply disappeared from the assemblage at this time.

Between 1.0 and 0.14 ka, *Abiskomyia* became far more abundant and *Pseudodiamesa* reappeared in the assemblage, although in low relative abundance, while the warmer taxa which had appeared around 1.6 ka decreased to very low values. As of 0.14 ka the relative abundance of *Abiskomyia* decreased as *Paracladius* and *Sergentia* increased. All of the warmer taxa that were present during the early-Holocene, with the exception of *Procladius*, were still present in the assemblage, although their relative abundances did not significantly increase in the recent sediments.

6.1.3. Ordination of the chironomid assemblages

The first two components of a principal components analysis (PCA) used to summarize the trends in chironomid assemblages and sediment parameters through time explained 25% and 13% of the total variance (Fig. 5). Tanytarsina-other, *Micropsectra* spp., *P. nigra* and *H. maeaeeri* had positive loadings on the first axis whereas *Abiskomyia*, *Pseudodiamesa*, *Paracladius*, *Sergentia* and *Zalutschia*-type B had negative loadings on this first axis.

The first component sample scores were highest and relatively constant up to 8.1 ka and then decreased until the most recent sediment (Fig. 6). The sample scores for the second component increased until 5 ka and then declined again until ~3.5 ka, although they remained positive. Between 3.5 ka and 2.0 ka, the

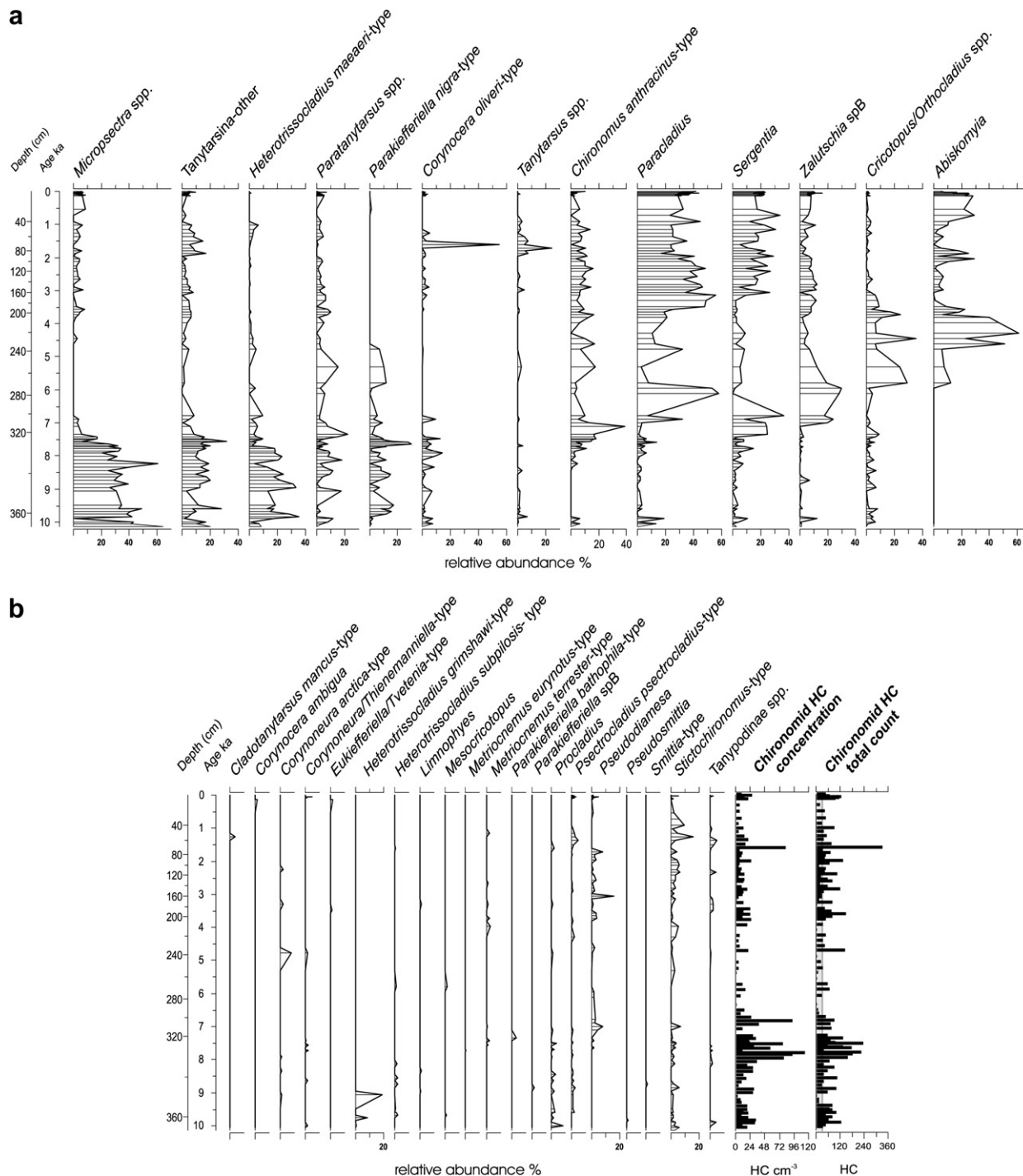


Fig. 4. Time series plots of the relative abundances (%) of all chironomid taxa present in Lake KR02 over the last 10,200 years. The (a) dominant chironomid taxa and (b) rarer chironomid taxa are presented only for levels with count sums over 30 head capsules. The dominant taxa are presented according to the order in which they appear in the core, whereas the rare taxa are presented alphabetically according to taxon name. Chironomid head capsule (HC) concentrations and count sums for all levels are also included. The light grey band indicates the 30 HC count threshold, samples with HC counts below this threshold were not included in the analysis. The dark grey band indicates the 40 HC count threshold, 9 levels with counts between 30 and 40 HC were included in the analysis.

scores of the second component fluctuated just above zero, then became negative at 2.0 ka. Scores were lowest at ~1.2 ka, rising slightly since that time.

6.2. Interpretation of biological paleo-production

The pollen, diatom and chironomid concentrations and accumulation rates, interpreted as production records, all indicate

higher production prior to 6.5 ka although diatom and BSI concentrations show some differences due to changes in species compositions (Podrisky and Gajewski, 2007; Peros and Gajewski, 2008; Figs. 3 and 7). Accumulation rates and concentrations of all three groups tend to be lower in the past 6.5 ka, although there were coherent variations even at these low values in the mid- to late-Holocene (Fig. 7). All three groups show synchronous peaks in production at ~7.0 and again in the recent sediment, and the

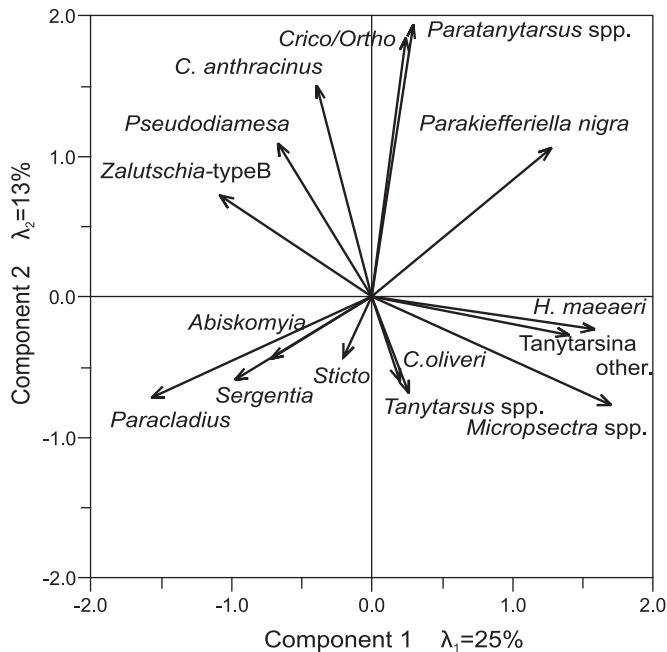


Fig. 5. Principal component biplot of the chironomid taxa (relative abundance %). Levels with more than 30 head capsules and only taxa with a mean relative abundance >1% averaged overall levels were included. *C. anthracinus* = *Chironomus anthracinus*-type, *C. oliveri* = *Corynocera oliveri*-type, *Crico/Ortho* = *Cricotopus/Orthocladius* spp., *H. maeaeeri* = *Heterotrissocladius maeaeeri*-type, *Sticto* = *Stictochironomus*-type.

aquatic organisms show elevated values relative to the previous millennia between ~4 and 1 ka.

6.3. Paleoenvironmental reconstructions

Both chironomid-based WAPLS and MAT methods produced similar long-term trends in July temperature reconstructions, although the MAT technique generally predicted on average 0.9 °C warmer temperatures than the WAPLS technique (Fig. 6). The sample specific error estimates were on average 2 °C (+/–0.1 °C) and 2.4 °C (+/–0.15 °C) for the WAPLS and MAT respectively. The early-Holocene, from 10.2 ka to ~6.7 ka, was indicated to be the warmest period, with temperatures between 9.6 and 11.7 °C and 10.9 and 12.7 °C for the WAPLS and MAT reconstructions, respectively. This was followed by a long-term decrease in July temperatures until 1.6 ka. The chironomid-based MAT reconstructed large temperature fluctuations during this time, with temperatures rising from 6 to 11 °C in the span of only 500 years, whereas the WAPLS model reconstructed a more gradual decrease in temperature from 5.7 to 4 ka followed by a more stable cool period from 4.0 ka to 1.6 ka. Temperatures rose rapidly at 1.6 ka, remaining relatively warm until ~1.0 ka; this is especially noticeable in the MAT reconstruction. This period was followed by an abrupt transition into a cool period, reaching similar cold temperatures as those experienced around 2 ka. From 0.14 ka to recent times temperatures rose slightly. The chironomid-derived WAPLS and MAT models generated average temperatures for the 5 samples between 1971 and 2000 of 7.7 °C and 8.1 °C for the WAPLS and MAT models, respectively, compared to Ulukhaktok (Holman) July air temperature normals from 1971 to 2000 of 9.2 °C (1971–2000 normals, Meteorological Survey of Canada, 2006).

A pH reconstruction based on sediment carbonate and BSi weight% (Fortin and Gajewski, 2009a,b) indicates oscillations in lake water pH, with peak values of more alkaline periods prior to ~9.9 ka, between 8.0 and 7.5 ka and again between 4.5 and 5.5 ka.

Lake water pH inferred for the most recent sediment was 7.1, which is comparable to the pH of 7.3 which was measured at the lake at the time the core was collected.

7. Discussion

7.1. Low frequency climatic change during the Holocene

The chironomid-based mean July air temperature reconstruction indicated a warmer early- to mid-Holocene prior to ~7.5 ka and a subsequent long-term cooling marked by a number of warming and cooling events of differing duration. The chironomid-derived mean July air temperature, supported by increases in both organic and BSi production and AR, indicated a warming over the last 140 years. Although the sample specific errors for the air temperature reconstructions are relatively large, the temperatures estimated for the early-Holocene (before ~7 ka) remain significantly higher than those estimated for the mid-Holocene (5–~1.6 ka), and those estimated after 1 ka. Although the broad-scale trends in production indices are coherent with the chironomid-based reconstruction, higher frequency variability is not easily associated with the inferred temperatures.

A pollen-based mean July air temperature reconstruction also shows a similar pattern (Fig. 6) with a long-term increase in relative abundance of pollen taxa characteristic of high-Arctic vegetation starting around 8.0 ka and continuing throughout the Holocene (Peros and Gajewski, 2008). Interpretation of the diatom record is less straightforward, as factors such as within-lake or post-depositional dissolution may have affected the diatom assemblages and concentrations present in the sediment, most notably in the bottom half of the core (Podrisky and Gajewski, 2007; Fig. 7).

Sediment organic and BSi AR and weight% were generally lowest in the warmer early-Holocene (notably 9.5–8.1 ka) and highest during the cooler late-Holocene (after 4 ka). Similar organic profiles, where organic content increases in the sediment through the Holocene, are found in the sediment records of Lake PW03, Prescott Island and Lake RS29, Somerset Island in Nunavut (Finkelstein and Gajewski, 2007; Paull, 2008). It is unclear why organic matter (AR and weight%) is increasing at these sites through the Holocene, as numerous proxy records clearly indicate a long-term cooling throughout the region (summarized in Gajewski and Atkinson, 2003; Kaufman et al., 2004). These broader trends in organic accumulation may be related to lake ontogeny rather than a response of the ecosystem to direct external forcing (Deevey, 1984; Battarbee et al., 2005; Anderson et al., 2008). The organic matter building up through time in the lacustrine system could be the result of a number of factors such as positive ratios of production vs diagenesis of the organic matter, or changes in the basin morphometry through time. The accumulation of organic matter in the sediment would therefore not be simply due to climate-induced increases in lacustrine ecosystem productivity but rather to the natural evolution of the lake as it ages (Deevey, 1984). Although it is not clear that this process applies in these oligotrophic lakes with short growing seasons, it does remain one working hypothesis to explain the building up of organic matter in these systems.

Within this long-term increasing trend of organic matter at Lake KR02, there are periods of relatively higher organic production, especially noticeable in the organic percentage and AR curves at 10.5–9.5 ka, 7.2–6.5 ka, 4.0–1.7 ka. These periods correspond to similar increases in the chironomid, pollen and diatom concentration and AR curves, as well as BSi percentages (Fig. 7). These smaller-scale variations in AR are reflecting increases in organic production by these and presumably other organisms in the watershed and the lake, and are a consequence of changes in environmental conditions superimposed on the build-up through time of organic matter in the system.

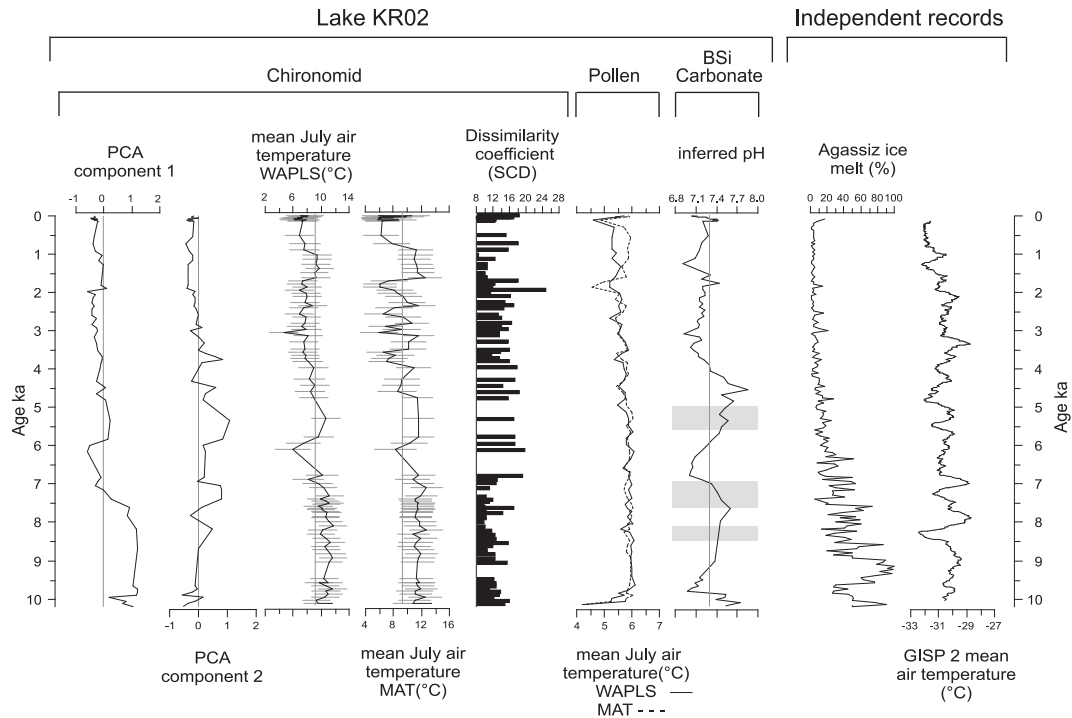


Fig. 6. Lake KR02 chironomid-based PCA sample scores, chironomid and pollen (Peros and Gajewski, 2008) inferred mean July air temperature (°C) and sediment BSi and carbonate inferred pH compared to independent climatic records of Agassiz ice melt % (Fisher et al., 1995) and central Greenland mean annual air temperatures (Alley, 2004). Both weighted average partial least squares (WAPLS) and modern analogue technique (MAT) generated temperature reconstructions are presented for the chironomid-based reconstructions. Horizontal grey lines represent the sample specific error estimates (°C). The vertical grey line at 9.2 °C in the inferred temperature plots is the 1971–2000 July air temperature Normal for Ulukhaktok (Holman), the closest weather station, (Meteorological Survey of Canada, 2006). Squared chord distance (SCD) dissimilarity coefficient for the chironomid-based MAT reconstruction is presented. Horizontal bars represent zones of inferred diatom dissolution (Podrisky and Gajewski, 2007).

The chironomid- and pollen-based mean July air temperatures at Lake KR02 both showed a cooling trend through the Holocene (Fig. 6). The chironomid-based temperature reconstruction also shows transitions at the same time as the production indices,

including that of pollen production, although this is not as evident in the pollen-based July temperature reconstruction. However, the range of predicted temperatures based on the pollen record is much narrower than that of the chironomid-based temperatures, and the

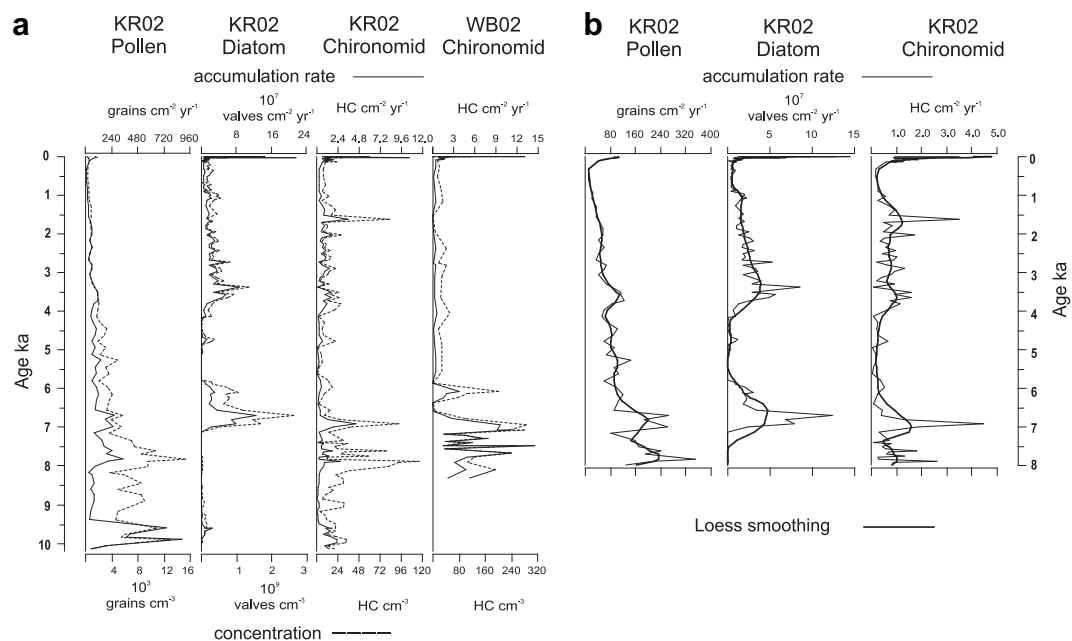


Fig. 7. (a) Production profiles of pollen, diatoms, and chironomids spanning the Holocene at Lake KR02 and production of chironomids at Lake WB02 in Northern Victoria Island (Fortin and Gajewski, 2009b). Concentrations (dotted line) and accumulation rates (solid line) are both included. (b) Production profiles truncated at 8 ka of the pollen, diatom, and chironomid proxies present in the sediment record of Lake KR02 are presented to illustrate the variability when values are low. A loess smoothing was added to each curve (thick line).

pollen-based temperatures were systematically cooler, up to 5 °C, than those based on chironomid assemblages (Fig. 6). Francis et al. (2006) and Briner et al. (2006) noted that chironomid-inferred July air temperatures for sites on Baffin Island were comparably higher than those based on pollen. These authors suggest that their pollen records, which were shorter than the chironomid records, may not have actually “captured” the highest temperatures of the Holocene thermal maximum (HTM). However, this is not the case for Lake KR02, as the differences at Lake KR02 between chironomid- and pollen-based mean July air temperatures continue into the most recent sediments, with chironomid-inferred temperatures on average 2 °C warmer than the pollen-based ones. The mean July air temperature normal of 9.2 °C, taken from the Ulukhaktok (Holman) meteorological station, is closer to the chironomid-inferred mean July air temperatures for this same period (7.6° and 8.0 °C, based on the WAPLS and MAT respectively) than the values of 5.5 °C (WAPLS) and 5.8 °C (MAT) predicted from the pollen. To better understand this difference in estimated temperatures through the Holocene at Lake KR02, we looked at the geographical distribution of the modern analogues chosen for both the pollen and chironomid records. The fossil pollen record most closely resembles (best analogues) modern assemblages from Boothia Peninsula, western Victoria Island and Somerset Island, all located between 70 and 73° latitude, in the low to middle Arctic. The chironomid fossil assemblages have close analogues from northern British Columbia and the southern Yukon for the early-Holocene and from Tuktoyaktuk, Boothia Peninsula and Somerset Island for the middle- to late-Holocene. Thus, the chironomid fossil record has modern analogues located further south than the pollen fossil assemblages, which explains the inferred warmer temperatures. The distribution of sites for both the pollen and chironomids have similar northern reaches, however the pollen data used by Peros and Gajewski (2008) does not extend further south than Boothia Peninsula, since boreal forest pollen would clearly not be chosen as acceptable analogues for the tundra pollen assemblages in the KR02 core. Although this analysis explains why the temperature reconstructions are different, it does not explain why chironomid assemblages find good analogues so far south. It may be due to the lack of chironomid samples from parts of the Canadian Arctic, so best analogues are found to the south, where widely distributed chironomids are living. Alternatively, it may be that Arctic plants, also widely distributed, are excluded by competition from the boreal zone, although they may be able to tolerate the warmer conditions. Other hypotheses could be offered, but this difference in reconstructions between different groups of organisms requires further study, and this exercise shows that we need a better understanding of the biogeography of both groups to resolve this issue.

7.2. Terrestrial and aquatic responses to high-frequency climatic changes

Prior to 10.2 ka, magnetic susceptibility values were very high, during a short period of ~300 years immediately following the formation of the lake basin. High values of MS immediately after deglaciation have been found in other sediment cores and can be associated with lake sediment receiving glacial outwash (Finkelstein and Gajewski, 2007) and rapid inwash from slopes surrounding the lake. Chironomid species richness is very high in this portion of the core, implying rapid colonization of the site by chironomids and the immediate establishment of the species pool in the lake. This indicates a rapid dispersal of chironomids to northwestern Victoria Island at a time when the Laurentide ice sheet was to the south, implying either long-distance transport or movement to the site from areas far to the south, or an origin from refugia somewhere in the western Arctic.

Between 10.2 ka and ~7.5 ka, the warmest period in western Victoria Island, the chironomid assemblages were dominated by warm-tolerant taxa and chironomid production and accumulation rates were higher than at any other time. Chironomid-based temperature estimates were up to 4 °C warmer than the temperatures inferred for the most recent 140 years. Closest modern analogues for the fossil chironomid assemblages during this time were found in northern British Columbia, southern Yukon and the Tuktoyaktuk Peninsula. Peaks in chironomid production in the earlier Holocene, between 10.2–9.5 ka and 8.3–7.5 ka, are largely due to increases in production of the warm-tolerant taxa. These peaks were synchronous with those of the pollen concentration and pollen accumulation rates (AR) and with increases in the organic AR and percentages in the lake at 10.2 ka and to a smaller extent at 8.3 ka (Figs. 3 and 7).

A small peak in diatom production also occurred between 9.9 and 9.6 ka (Fig. 7a). However, despite the enhanced production in the chironomid and pollen data, diatom concentrations remained very low between 8.3 and 7.5 ka. Podritske and Gajewski (2007) observed significant valve fragmentation and very low overall diatom concentrations prior to 7.0 ka (Fig. 7). They proposed three hypotheses for the presence of diatom-free zones during these times: dissolution, dilution due to increased runoff, and cool temperatures. Given the high values of both pollen and chironomid AR during periods of low diatom concentrations and the warm reconstructed temperatures, we can now dismiss cool temperatures (which presumably would have led to the lake being ice covered for long time periods) as a possible cause. There is no evidence for valve dilution in the sediment due to increased runoff as a potential cause either, as the concentrations and AR of pollen and chironomids remained high during these times of low diatom concentrations. This leaves dissolution as a probable cause of the low values, perhaps due to an increase in lake water pH causing post-depositional dissolution, or by the dissolving of the diatoms in the water or sediment surface due to low silica concentrations in the water. Podritske and Gajewski (2007) also note important valve fragmentation between 8.5–8.2 ka and 7.6–7.0 ka (Fig. 7) and indeed the inferred pH profile (Fig. 6), based on sediment carbonate and biogenic silica weight%, indicates highest pH values corresponding to the times of valve fragmentation and very low diatom concentrations. Diatom dissolution can occur at higher pH (e.g., Ryves et al., 2006) and the diatoms which were found in the dissolved areas of the core were alkaliphilic taxa (Podritske and Gajewski, 2007). However, the mechanisms behind diatom dissolution are not yet well understood; therefore the validity of this third hypothesis needs to be further explored.

Kaufman et al. (2004) interpreted the HTM as having occurred in the western Arctic between 8.9 ± 2.1 ka and 5.9 ± 2.6 ka. We are now able to better constrain this period between 9.9 and 7.5 ka for this site on western Victoria Island, as all of the proxies in this well-dated core concur to indicate this is the warmest period. At Lake WB02 on Northern Victoria Island, chironomid production was also highest in the early-Holocene (Fortin and Gajewski, 2009b). Chironomid records from Lake CF3 on Baffin Island indicate temperatures ~5 °C warmer between 10 and 8.5 ka (Briner et al., 2006), which is comparable to the timing of the warming at KR02.

A significant transition occurred at Lake KR02 between 7.5 and 6.5 ka, which is interpreted as a shift towards a cooler climate. This transition is seen in the chironomid assemblages, where a community dominated by warmer-tolerant taxa was replaced by one dominated by colder-tolerant taxa. For example, the warm-tolerant taxa of the Tanytarsina subtribe nearly disappeared and *Paracladius*, typical for cold water, and *Sergentia*, typical for cold to moderate water, appeared (Fig. 4). Similarly, the pollen assemblages are also interpreted as indicating a cooling. Based on the chironomid record it seems that this transition can be divided into

three parts. As the cooling began (~7.5 ka), the warm-water taxa decreased in relative abundance quite abruptly and were initially replaced by *C. anthracinus*-type. *C. anthracinus*-type is a taxon which is usually found in profundal areas in lakes. It was present in the earliest assemblages, but was later reduced in abundance, perhaps because it was unable to compete for food or other resources with the other profundal taxa *Micropsectra* spp. and *Heterotrissocladius* spp. (Larocque et al., 2006; Brooks et al., 2007) also present in the core in the warmer early-Holocene. Changing environmental conditions, as quantified in the chironomid- and pollen-(MAT) based air temperature reconstructions, are associated with a decrease in abundance of *Micropsectra* spp. and Tanytarsinae, which were rapidly replaced by *C. anthracinus*-type. The high abundance of this taxon at this time may be indicative of a large change occurring in the environment. *C. anthracinus*-type was also present in the sediment record of Lake WB02 in northern Victoria Island at roughly the same time (Fortin and Gajewski, 2009a,b), which for that region also corresponds to the timing of a major change in the chironomid assemblages. Colder-tolerant taxa quickly took over and dominated the assemblage. These cold-water taxa became so productive at ~6.9 ka that there was a spike in overall chironomid AR and concentrations, and this during an inferred cool period. Similar spikes are seen in the pollen and diatom production. These increases in production appear to be the ecosystem response to changes in climatic conditions, and are not due to an amelioration of environmental conditions, as climate in fact appears to be cooling at this time. This transition coincides with the disappearance of the Laurentide Ice Sheet to the south, beginning with the collapse of the ice sheet in the region that today is Hudson Bay around 8.2 ka, to the final melting of the ice in northern Québec around 6 ka (Dyke, 2004). The atmospheric circulation changed at that time, leading to a cooling in the Arctic following a period of warm air transport to the Arctic.

The chironomid- and pollen-based mean July air temperatures between 6.4 and 4 ka remain cooler than those reconstructed prior to 7.5 ka. The chironomid assemblages during this time resembled the assemblages found in low and middle Arctic lakes from Tuktoyaktuk, the Boothia Peninsulas and Somerset Island. The chironomid-inferred air temperature profile, however, shows more variability than the pollen-based reconstruction, although the low concentrations of head capsules in the sediments of this time make the reconstructions less reliable. Terrestrial and aquatic production remained low during this cooling and even though there was a decrease in organic AR and percentages when compared to the values at ~6.8 ka, values do remain higher than those in the early-Holocene. *Abiskomyia* may have arrived on Victoria Island at ~6.0 ka, as it entered the assemblage at both Lake KR02 and Lake WB02 (Northern Victoria) at this time, dominating the assemblages at both lakes in the later Holocene (Fortin and Gajewski, 2009b).

The period between 6.5 and 4 ka corresponds to a period with the fewest modern analogues. This suggests that the modern dataset used may not have contained sufficient modern sites with colder air temperatures (see Fortin and Gajewski, 2009b). The cooling observed at KR02 in the mid-Holocene (Fig. 6) is also observed in records from the Agassiz Ice core on northern Ellesmere (Fisher et al., 1995), as well as inferred from decreases in chironomid, pollen and/or diatom production in lakes from northern Victoria Island, northern Boothia Peninsula, Somerset Island and Prince of Wales Island (Gajewski, 1995; LeBlanc et al., 2004; Finkelstein and Gajewski, 2007; Zabenskie and Gajewski, 2007; Fortin and Gajewski, 2009b).

Another environmental change occurred at 4.0 ka, which triggered an increase in production of the aquatic organisms, as well as an increase in sediment organic content extending over the next two thousand years. After 4.0 ka, the chironomid assemblages were

still dominated by the same cold-water taxa as before, but warmer-tolerant taxa which were present in the early-Holocene returned to the assemblages, albeit in low relative abundances. Although interpretation of the chironomid assemblages indicates large changes between 4.0 ka and 2.0 ka, the quantitative reconstructions do not; they indicate continued cool conditions, as does the pollen-based mean July air temperatures record. The chironomid-inferred temperatures indicate more or less constant temperatures between 4 ka and 2 ka with some high-frequency variability, whereas the pollen-based air temperatures show a continuation of the same cooling trend which had been occurring since ~7.5 ka.

After ~2.5 ka, both the chironomid-based and pollen-based temperature reconstructions (especially seen in the MAT based reconstructions in both cases) indicate an abrupt cooling event. Temperatures quickly rose around 1.6 ka and remained high until ~1.0 ka in both the pollen and chironomid reconstructions. From 1.6 to 1.0 ka the chironomid community resembled those assemblages currently found in northern British Columbia and warmer lakes of the Tuktoyaktuk Peninsula. Similarly, diatom richness and production both increased at this time, as did the heterogeneity of the life strategies and living habitats of the diatom taxa found within the assemblages at this time (Podrifske and Gajewski, 2007). Distinct changes in the diatom community also occurred between 1.4 and 0.95 ka. Inferred warming periods, said to correspond to the Medieval Warm Period (MWP), were noted as having occurred broadly between 1.5 and 0.6 ka in the central Arctic on Boothia Peninsula, Prince of Wales, Southampton Island and northern Victoria Island (Overpeck et al., 1997; LeBlanc et al., 2004; Finkelstein and Gajewski, 2007; Fortin and Gajewski, 2009b; Rolland et al., 2008).

A cooling began around 1.0–0.85 ka. This is inferred from the chironomid record and temperature reconstruction, as well as by the diatom assemblage, diversity and production records. The chironomid assemblages during this time were similar to those currently found in the Middle Arctic. This cooling may correspond to the Little Ice Age (LIA) which was observed at roughly the same time at a number of diatom (Wolfe, 2003; LeBlanc et al., 2004) and pollen records (Finkelstein and Gajewski, 2007) across the Arctic. Chironomid-based studies from Baffin Island (Briner et al., 2006; Francis et al., 2006) were unable to detect the LIA in their records, but a cooling was recorded in the midge record from Southampton Island between 0.6 and 0.3 ka (Rolland et al., 2008) and from southern Victoria Island between 0.9 and 0.3 ka (Porinchu et al., 2009b).

From ~0.14 ka, the pollen and chironomid-derived temperature reconstructions, as well as the production records of all three proxies seem to indicate a warming that continues until the most recent times. Organic and BSi percentages and AR also increased at this time. This post-Little Ice Age warming is now well documented across the Arctic (e.g., LeBlanc et al., 2004; Smol et al., 2005; Peros and Gajewski, 2008; Fortin and Gajewski, 2009b; Kaufman et al., 2009). However temperatures inferred and measured for recent times at Lake KR02 remain up to 4 °C cooler than those of the early- to mid-Holocene warm period.

8. Conclusion

Multi-proxy analyses of sediment cores provide a more complete understanding of past climatic conditions than those obtained from only one source. For Lake KR02 on western Victoria Island, interpretations of the pollen and diatom records included some discrepancies regarding the climatic conditions at this lake over the Holocene period. The chironomid data presented here for this lake were able, in part, to reconcile the differences between the pollen and diatom records, and also elucidate the climatic history of the lake. The early-Holocene prior to 6.5 ka was a warm period of high aquatic and terrestrial production. From 5.5 to 4 ka there was

a cooling period, followed by change in environmental conditions at 4 ka and cool temperatures lasting the next two millennia. An abrupt warming occurs at 1.6 ka, followed by an abrupt cooling at ~1.0 ka and a final increase in temperatures, starting at 0.14 ka through to recent times. Temperatures prior to 6.5 ka are the warmest for the Holocene. The climate as recorded at lake KR02 also corresponds to the climate inferred from independent records from other sites on Victoria Island and across the Arctic.

Acknowledgements

This work was funded by grants from Natural Sciences and Engineering Research Council of Canada and the Canadian Foundation for Climate and Atmospheric Sciences. Logistic support was provided by the Polar Continental Shelf Project and this is PCSP publication number 02209. We would like to acknowledge the help of Paul Hamilton, Giselle Bouchard and Michelle LeBlanc in the field, and Brett O'Neil, Rebecca Ravindra, Tara Paull and Jess McGuinness for help in the lab. Thank you to the reviewers for their helpful comments.

References

- ACIA, 2005. Arctic Climate Impact Assessment. Cambridge University Press, New York.
- Alley, R.B., 2000. The Younger Dryas cold interval as viewed from central Greenland. *Quaternary Science Reviews* 19, 213–226.
- Alley, R.B., 2004. GISP2 ice core temperature and accumulation data. In: IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series #2004-013. NOAA/NGDC Paleoclimatology Program, Boulder, CO, USA.
- Anderson, N.J., Brodersen, K.P., Ryves, D.B., McGowan, S., Johansson, L.S., Jeppesen, E., Leng, M.J., 2008. Climate versus in-lake processes as controls on the development of community structure in a low-arctic lake (South-West Greenland). *Ecosystems* 11, 307–324.
- Barley, E.M., 2004. Paleoclimate analysis of southwestern Yukon Territory using subfossil chironomid remains from Antifreeze Pond. MSc. Thesis, Simon Fraser University, Burnaby, BC.
- Barley, E.M., Walker, I.R., Kurek, J., Cwynar, L.C., Mathewes, R.W., Gajewski, K., Finney, B.P., 2006. A northwest North American training set: distribution of freshwater midges in relation to air temperature and lake depth. *Journal of Paleolimnology* 36, 295–314.
- Battarbee, R.W., John Anderson, N., Jeppesen, E., Leavitt, P.R., 2005. Combining palaeolimnological and limnological approaches in assessing lake ecosystem response to nutrient reduction. *Freshwater Biology* 50, 1772–1780.
- Bouchard, G., Gajewski, K., Hamilton, P.B., 2004. Freshwater diatom biogeography in the Canadian arctic archipelago. *Journal of Biogeography* 31, 1955–1973.
- Briner, J.P., Michelutti, N., Francis, D.R., Miller, G.H., Axford, Y., Wooller, M.J., Wolfe, A.P., 2006. A multi-proxy lacustrine record of Holocene climate change on northeastern Baffin Island. *Arctic Canada* 65, 431–442.
- Brooks, S.J., Langdon, P.G., Heiri, O., 2007. The Identification and Use of Palaeoartctic Chironomidae Larvae in Palaeoecology. QRA Technical Guide No.10. Quaternary Research Association, London.
- CAVM team, 2003. Circumpolar Arctic Vegetation Map. Scale 1: 7,500,000. Conservation of Arctic Flora and Fauna (CAFF) Map No.1. U.S. Fish and Wildlife Service, Anchorage, Alaska.
- Deevey, E.S., 1984. Stress, strain, and stability of lacustrine ecosystems. In: Haworth, E.Y., Lund, J.W.G. (Eds.), *Lake Sediments and Environmental History*. University of Minnesota Press, Minneapolis, pp. 203–229.
- Dyke, A.S., 2004. An outline of North American deglaciation with emphasis on central and northern Canada. In: Ehlers, J., Gibbard, P.L. (Eds.), *Quaternary Glaciations—Extent and Chronology*. Elsevier, Oxford, pp. 373–424.
- Finkelstein, S.A., Gajewski, K., 2007. A palaeolimnological record of diatom-community dynamics and late-Holocene climatic changes from Prescott Island, Nunavut, central Canadian Arctic. *Holocene* 17, 803–812.
- Fisher, D.A., Koerner, R.M., Reeh, N., 1995. Holocene climatic records from Agassiz ice Cap, Ellesmere Island, NWT, Canada. *Holocene* 5, 19–24.
- Fortin, M.-C., Gajewski, K., 2009a. Assessing the use of sediment organic, carbonate and biogenic silica content as indicators of environmental conditions in Arctic lakes. *Polar Biology*. doi:10.1007/s00300-009-0598-1.
- Fortin, M.-C., Gajewski, K., 2009b. Holocene climate change and its effect on lake ecosystem production on Northern Victoria Island, Canadian Arctic. *Journal of Paleolimnology*. doi:10.1007/s10933-009-9326-7.
- Francis, D.R., Wolfe, A.P., Walker, I.R., Miller, G.H., 2006. Interglacial and Holocene temperature reconstructions based on midge remains in sediments of two lakes from Baffin Island, Nunavut, Arctic Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology* 236, 107–124.
- Frisch, T., Trettin, H.P., 1991. Precambrian Successions in the northernmost part of the Canadian Shield. In: Trettin, H.P. (Ed.), *Geology of the Innuition Orogen and Arctic Platform of Canada and Greenland*. Geological Survey of Canada, pp. 109–115. Ottawa.
- Gajewski, K., 1995. Modern and Holocene pollen assemblages from some small arctic lakes on Somerset Island, NWT, Canada. *Quaternary Research* 44, 228–236.
- Gajewski, K., Atkinson, D., 2003. Climatic change in northern Canada. *Environmental Reviews* 11, 69–102.
- Gajewski, K., Bouchard, G., Wilson, S.E., Kurek, J., Cwynar, L.C., 2005. Distribution of Chironomidae (Insecta: Diptera) head capsules in recent sediments of Canadian Arctic lakes. *Hydrobiologia* 549, 131–143.
- Heiri, O., Lotter, A.F., 2001. Effect of low count sums on quantitative environmental reconstructions: an example using subfossil chironomids. *Journal of Paleolimnology* 26, 343–350.
- Heiri, O., Ekrem, T., Willassen, E., 2004. Larval head capsules of European *Microspectra*, *Paratanytarsus* and *Tanytarsus* (Diptera: Chironomidae: Tanytarsini). Version 1.0. <http://www3.bio.uu.nl/palaeo/Chironomids/Tanytarsini/intro.htm>.
- Kaufman, D.S., Ager, T.A., Anderson, N.J., Anderson, P.M., Andrews, J.T., Bartlein, P.J., Brubaker, L.B., Coats, L.L., Cwynar, L.C., Duvall, M., Dyke, A.S., Edwards, M.E., Eisner, W.R., Gajewski, K., Geirsdóttir, A., Hu, F.S., Jennings, A.E., Kaplan, M.R., Kerwin, M.W., Lozhkin, A.V., MacDonald, G.M., Miller, G.H., Mock, C.J., Oswald, W.W., Otto-Bliesner, B.L., Porinchu, D.F., Rühland, K., Smol, J.P., Steig, E. J., Wolfe, B.B., PARCS working group, 2004. Holocene thermal maximum in the western Arctic (0–180°W). *Quaternary Science Reviews* 23, 529–560.
- Kaufman, D.S., Schneider, D.P., McKay, N.P., Ammann, C.M., Bradley, R.S., Briffa, K.R., Miller, G.H., Otto-Bliesner, B.L., Overpeck, J.T., Vinther, B.M., Abbott, M., Axford, Y., Bird, B., Birks, H.J.B., Björne, A.E., Briner, J., Cook, T., Chipman, M., Francus, P., Gajewski, K., Geirsdóttir, A., Hu, F.S., Kutchko, B., Lamoureux, S., Loo, M., MacDonald, G., Peros, M., Porinchu, D., Schiff, C., Seppä, H., Thomas, E., 2009. Recent warming reverses long-term arctic cooling. *Science* 325, 1236–1239.
- Larocque, I., 2001. How many chironomid head capsules are enough? A statistical approach to determine sample size for palaeoclimatic reconstructions. *Palaeogeography, Palaeoclimatology, Palaeoecology* 172, 133–142.
- Larocque, I., Pienitz, R., Rolland, N., 2006. Factors influencing the distribution of chironomids in lakes distributed along a latitudinal gradient in northwestern Quebec, Canada. *Canadian Journal of Fisheries and Aquatic Sciences* 63, 1286–1297.
- Larocque, I., Rolland, N., 2006. Le guide visuel des Chironomides sub-fossiles, du Québec à l'Île d'Ellesmere. Université du Québec, Institut national de la recherche scientifique, Québec. Rapport de recherche No R-900.
- LeBlanc, M., Gajewski, K., Hamilton, P.B., 2004. A diatom-based Holocene palaeoenvironmental record from a mid-arctic lake on Boothia Peninsula, Nunavut, Canada. *Holocene* 14, 417–425.
- Meteorological Survey of Canada, 2006. Canadian climate normals 1971–2000: Ulukhatok. http://www.climate.weatheroffice.ec.gc.ca/climate_normals/results_e.html.
- Oliver, D.R., Roussel, M.E., 1983. The Genera of Larval Midges of Canada. Diptera: Chironomidae. The Insects and Arachnids of Canada 11. Agriculture Canada, Ottawa.
- Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Case, R., Douglas, M., Finney, B., Gajewski, K., Jacoby, G., Jennings, A., Lamoureux, S., Lasca, A., Macdonald, G., Moore, J., Retelle, M., Smith, S., Wolfe, A., Zielinski, G., 1997. Arctic environmental change of the last four centuries. *Science* 278, 1251–1256.
- Paull, T.M., 2008. Diatom Biodiversity and Production in the Arctic. M.Sc. Thesis, University of Ottawa, Ottawa, Canada.
- Peros, M.C., Gajewski, K., 2008. Holocene climate and vegetation change on Victoria Island, western Canadian Arctic. *Quaternary Science Reviews* 27, 235–249.
- Podralske, B., Gajewski, K., 2007. Diatom community response to multiple scales of Holocene climate variability in a small lake on Victoria Island, NWT, Canada. *Quaternary Science Reviews* 26, 3179–3196.
- Porinchu, D.F., Rolland, N., Moser, K., 2009a. Development of a chironomid-based air temperature inference model for the central Canadian Arctic. *Journal of Paleolimnology* 41, 349–368.
- Porinchu, D.F., MacDonald, G.M., Rolland, N., 2009b. A 2000 year midge-based paleotemperature reconstruction from the Canadian Arctic archipelago. *Journal of Paleolimnology* 41, 177–188.
- Quinlan, R., Smol, J., 2001. Setting minimum head capsule abundance and taxa deletion criteria in chironomid-based inference models. *Journal of Paleolimnology* 26, 327–342.
- Rolland, N., Larocque, I., Francus, P., Pienitz, R., Laperrière, L., 2008. Holocene climate inferred from biological (Diptera: Chironomidae) analyses in a Southampton Island (Nunavut, Canada) lake. *The Holocene* 18, 229–241.
- Ryves, D.B., Battarbee, R.W., Juggins, S., Fritz, S.C., Anderson, N.J., 2006. Physical and chemical predictors of diatom dissolution in freshwater and saline sediments in North America and Greenland. *Limnology and Oceanography* 51, 1355–1368.
- Smol, J.P., Wolfe, A.P., Birks, H.H., Douglas, M.S., Jones, V., Korhola, A., Pienitz, R., Rühland, K., Sorvari, S., Antoniades, D., Brooks, S.J., Fallu, M.A., Hughes, A.M., Keatley, B., Laing, T., Michelutti, N., Nazarova, L., Nymann, M., Paterson, A.M., Perren, B.B., Quinlan, R., Rautio, M., Saulnier-Talbot, E., Siitonen, S., Solovieva, N., Weckström, J., 2005. Climate-driven regime shifts in the biological communities of arctic lakes. *Proceedings of the National Academy of Sciences of the United States of America* 102, 4397–4402.
- Walker, I.R., 1988. Late-Quaternary Palaeoecology of Chironomidae (Insecta: Diptera) in Lake Sediments in British Columbia. PhD Thesis, Simon Fraser University, Burnaby.

- Walker, I.R., 2000. The WWW field Guide to subfossil midges. <http://www.paleolab.ca/wwwguide/>.
- Walker, I.R., 2001. Midges: Chironomidae and related Diptera. In: Smol, J.P., Birks, H. J.B., Last, W.M. (Eds.), *Tracking Environmental Change Using Lake Sediments. Zoological Indicators*, vol. 4. Kluwer Academic Publishers, Dordrecht, pp. 43–66.
- Wiederholm, T., 1983. Chironomidae of the Holarctic region. Keys and diagnoses. Part 1. Larvae. *Entomologica Scandinavica Supplement* 19. Borgströms Tryckeri AB, Motala.
- Wolfe, A.P., 2003. Diatom community responses to late-Holocene climatic variability, Baffin Island, Canada: a comparison of numerical approaches. *Holocene* 13, 29–37.
- Zabenskie, S., Gajewski, K., 2007. Post-Glacial climatic change on Boothia Peninsula, Nunavut, Canada. *Quaternary Research* 68, 261–270.