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Pro- and postglacial invertebrate communities of Pingualuit Crater Lake, Nunavik (Canada), and their paleoenvironmental implications

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Abstract. Zoological remains were examined from the sediments of the Pingualuit Crater Lake, Nunavik, Canada. Our objective was to describe past climate events in the area of delayed deglaciation in northernmost Ungava Peninsula. Our record covers 3 separate sections of deglacial and postglacial invertebrate dynamics interrupted by laminated proglacial sediments and a basin-scale erosive slumping event. The abundance of animal remains in the ultra-oligotrophic and extremely deep arctic lake was low, but distinct faunal assemblages were found among the intervals, results implying that they were environmentally heterogeneous. The lowermost fine-grained interval (before 6850 calibrated years before present [cal BP]), revealed that Cladocera *Chydorus sphaericus*-type and *Bosmina (Eubosmina) longispina*-type were common in the lake, whereas Chironomidae were relatively rare. The dominance of *B. longispina*-type showed that planktonic communities were successful at the time, probably indicating more favorable climatic conditions than today soon after the last deglaciation (~7000 cal BP). In the middle interval (between ~6850 and 5750 cal BP), chironomids became more common and were dominated by *Heterotrissocladius subpilosus*-type and *Protanypus*, taxa that are characteristic of oligotrophic lakes. The extirpation of *B. longispina*-type suggests that planktonic invertebrate communities were not successful, probably because of predation by Arctic char. The presence of the chironomid *Oliveridia tricornis*-type during the late Holocene (between ~4200 and 600 cal BP) suggested general climate cooling. Our paleoclimatic conclusions on the regional environmental history suggest a stationary ice front in the initial stages of the Holocene, favorable climatic conditions in the mid-Holocene and a general late-Holocene cooling. Our records also indicate a subtle increase in nutrient availability throughout the Holocene. The paleoecological record from Pingualuit Crater Lake is valuable in describing the faunal history and biotic resilience in this environmentally extreme lake, which presently contains one of the world's softest and most transparent waters.

Key words: Chironomidae, Cladocera, Holocene, lake sediments, paleoclimate, paleolimnology, Pingualuit Crater Lake.

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Pingualuit Crater Lake is a unique ~1.4-Ma-old basin formed by a meteorite impact in northern Ungava Peninsula, Nunavik (Fig. 1). The lake also is known as the Crystal Eye of Nunavik because of its unusually clear water and the almost perfectly circular shape of its depression. As the most important feature of the Pingualuit National Park, Pingualuit Crater Lake is an extremely protected area (MDDEP 2005). Previous studies of the 246-m-deep lake indicated sediment fill up to 150 m (Bouchard

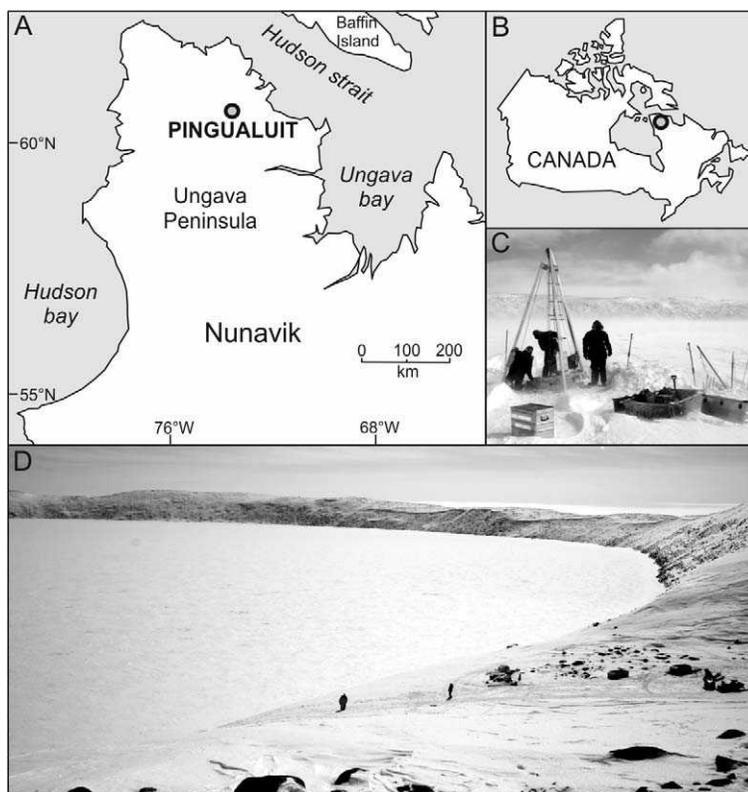


FIG. 1. Location of Pingualuit Crater Lake in the Ungava Peninsula, Nunavik, northern Québec (A) in Canada (B) and photographs showing sediment sampling using the UWITEC percussion piston corer (C) and the general aspect at the inner crater rim (D). Photos: V.-P. Salonen.

1989), with the topmost layers including fine-grained organic-rich intervals (Grönlund et al. 1989, Guyard et al. 2011).

The onset of deglaciation and the timing of the Holocene Thermal Maximum (HTM) were delayed in northern Québec compared to other parts of north-western and central Canadian Arctic (Kaufman et al. 2004, Kaplan and Wolfe 2006). The Laurentide Ice Sheet (LIS) persisted until ~8000 calibrated years before present (cal BP) in northernmost Québec (Dyke and Prest 1987, Occhietti et al. 2011), probably associated with the final deglaciation of Hudson Bay and Hudson Strait areas, but ice remnants still persisted on the Ungava Peninsula until between ~7000 and 6000 cal BP (Andrews et al. 1995). Because of its central location in northern Ungava, a climate reconstruction from Pingualuit Crater Lake would provide a better understanding of deglaciation timing and processes in this region of the Canadian Arctic.

Previous studies from Pingualuit Crater Lake have indicated the presence of sediment sequences rich in remains of aquatic organisms (Bouchard 1989, Black et al. 2012) and layers that may date back to the Late Pleistocene (Guyard et al. 2011). In our study, the

zoological component of the crater's past aquatic communities, including insects, crustaceans, and mites, is described. In general, the most abundant animal remains in freshwater sediments are the various skeletal fragments of water fleas (Crustacea: Cladocera), especially the head shields and shells of *Bosmina*, whereas the most abundant insect remains are the head capsules and mandibles of various midges, mostly Chironomidae (Frey 1964). Our goal was to find evidence for climate events and ice-free periods in this area of delayed deglaciation with a stationary ice front in the initial stages of the Holocene. Furthermore, our findings from this unique lake, which presently contains one of the world's softest and most transparent waters (Gantner et al. 2012), are ecologically valuable in describing the faunal history and biotic resilience in this environmentally extreme lake.

Methods

Study area

Pingualuit (also previously known as Nouveau-Québec or Chubb) Crater Lake (lat 61°17'N, long

73°41'W) is in the Ungava Peninsula of Nunavik, northern Québec, Canada (Fig. 1A, B). The crater was formed ~1.4 Ma ago (Grieve et al. 1991) on Archean bedrock dominated by granites and granitic gneisses (Currie 1965) and is a ~400-m-deep and 3.4-km-wide circular depression (Fig. 1D). Today, the depression is occupied by a transparent 246-m-deep and 2.8-km-wide lake, with a surface water level at 494 m asl. The Secchi depth was 33 m in August 2010 (Guyard et al. 2011) and the euphotic zone (1% irradiance) extends down to ~115 m (Gantner et al. 2012). The isolated lake (rim rising to 163 m above the lake surface and 120 m above the surrounding terrain) with its steep basin walls (30–35°) is ultra-oligotrophic and has a conductivity of 4.6 $\mu\text{S}/\text{cm}$ and pH of 5.9 (Bouchard 1989). The concentrations of Ca, Mg, K, and Na are 0.56, 0.16, 0.29, and 0.75 mg/L, respectively, whereas the concentration of total dissolved organic C (DOC) is 0.7 mg/L and chlorophyll *a* is <0.1 $\mu\text{g}/\text{L}$ (Gantner et al. 2012). The steep internal slopes are characterized by large blocks and boulders and almost completely lack vegetation and soils. The ice-free period lasts ~6 to 8 wk in summer, and the regional mean annual temperature is -6.3°C (Black et al. 2012).

Sampling and sediments

The uppermost ~9 m of sediments in Pingualuit Crater Lake was cored from the frozen lake in May 2007 using a UWITEC gravity and percussion piston coring system (UWITEC, Mondsee, Austria) (Fig. 1C) in the deepest part of the basin at a water depth of 244 m. In the laboratory, the cores were split, described, photographed, and analyzed for physical properties. More detailed descriptions on sediment sampling and preliminary laboratory treatments were provided by Guyard et al. (2011). Most of the core is characterized by light grey, inorganic, coarse, and highly deformed sediments reflecting glacial material. Three fine-grained intervals (Fig. 2) with light brown color and relatively high percentages of biogenic silica (BSi) were identified: facies IIIb between 780 and 710 cm, facies Ib between 270 and 257 cm, and facies Ia between 13.5 and 0 cm. For analysis of zoological macroremains, intervals IIIb and Ib (piston cores) were sliced at 0.5-cm intervals and section Ia (surface core) at 0.4-cm intervals for a total of 124 samples.

Chronology

Accelerator mass spectrometry (AMS) ^{14}C dating was used to date sections IIIb, Ib, and Ia. Bulk sediment samples were used because of the absence of terrestrial macrofossils (Guyard et al. 2011).

However, reliable chronologies from Arctic lake sediments are challenging to establish when bulk sediment samples are used (Abbott and Stafford 1996, Luoto et al. 2011, Salonen et al. 2011). The ^{14}C dates given by Guyard et al. (2011) indicate an age range of 33,915 to 34,785 cal BP for interval IIIb (3 dates), 6585 to 5625 cal BP for interval Ib (4 dates), and 3485 to 740 cal BP for interval Ia (9 dates). The dates obtained showed several reversals especially in glacial sediments, and the apparently old ^{14}C ages are a result of mixing of Holocene and redeposited older organic material, such as light-weight pollen and diatom valves, and, therefore, are not indicative of true age of deposition but rather reflect a mixing age (Guyard et al. 2011). The existing evidence indicates that unknown residual glaciated areas might have existed during the mid-Wisconsinan interstadial (MIS3) in the central parts of Ungava Peninsula (Kleman et al. 2010). Thus, the organic material found in glacial and lacustrine Pingualuit sediments (Richard et al. 1991, Guyard et al. 2011) would represent redeposition of older, most probably mid- and early Wisconsinan, sediments. This interpretation is consistent with recent micromorphological studies revealing remobilization processes of glacial sediments, especially in facies IIIb (HG, P. Francus [Institut National de la Recherche Scientifique, Eau Terre Environnement, Québec], GS-O, RP, and SH, unpublished data). Therefore, our invertebrate strata probably cover only the Holocene, and interval IIIb probably represents an initial stage of the lake's Holocene history (older than 6850 cal BP) with a strong proglacial influence, whereas intervals Ib and Ia probably represent later snapshots of lake history (Fig. 2). The same age-depth model was applied in our study as in the previous study by Guyard et al. (2011). In this model, interval IIIb represents sediments deposited before 6850 cal BP, interval Ib between 6850 and 5800 cal BP, and interval Ia between 4200 cal BP and the present. More details on the sediment dating and on the interpretation of the chronology are given by Guyard et al. (2011) and Black et al. (2012). Black et al. (2012) also described the diatom fossils discovered from the stratigraphy.

Fossil analysis

Subsamples of 0.7 to 7.9 g wet mass used for analysis of zoological macroremains (cf. Frey 1964) were sieved through a 100- μm sieve, a mesh size that depicts macro-sized animal remains, such as oribatids and chironomids, well (Verschuren and Eggermont 2007, de la Riva Caballero et al. 2010, Larocque et al. 2010). A smaller mesh size could be better for capturing the smallest fossil fragments of Cladocera

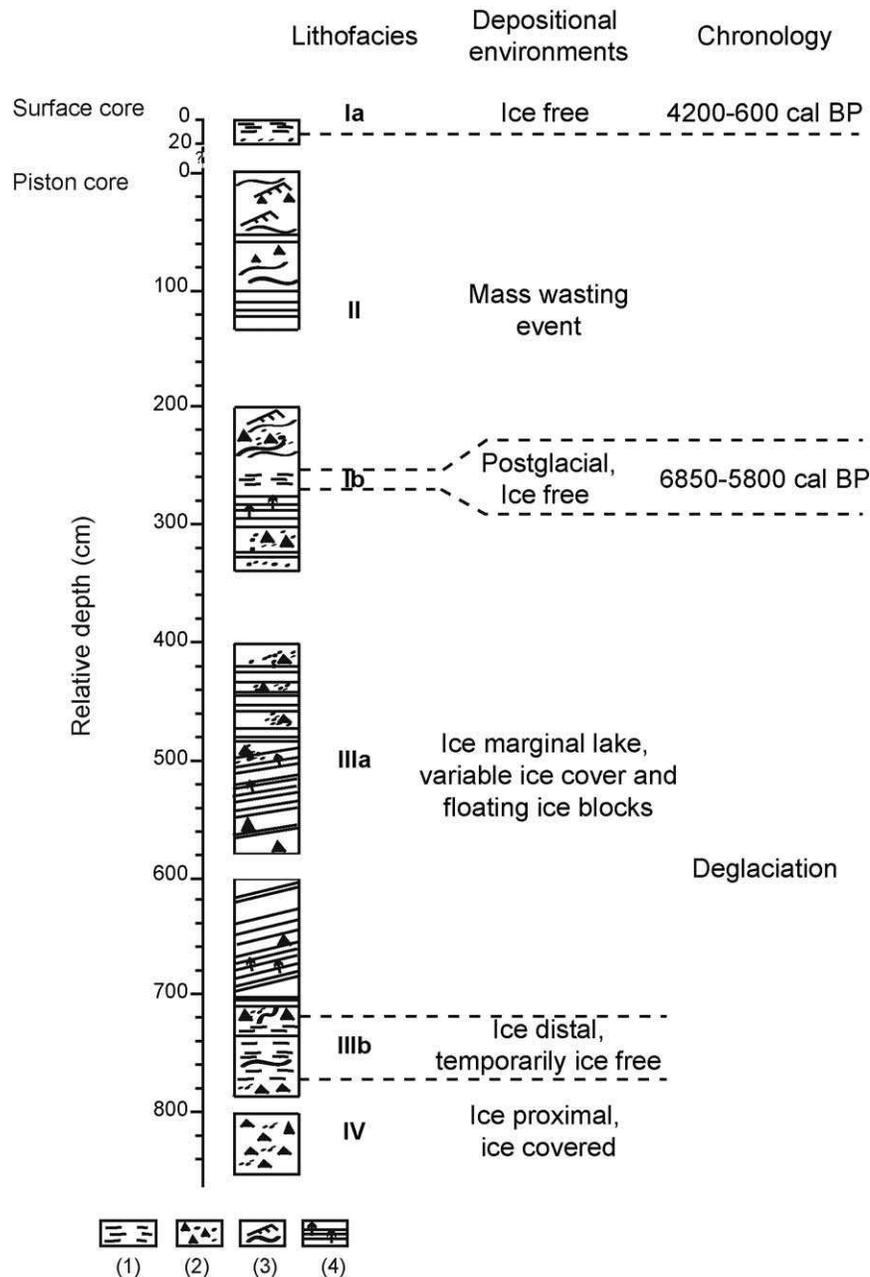


FIG. 2. General and simplified lithostratigraphy of the sediment retrieved in the deep basin of Pingualuit Crater Lake. (1) Organic-rich clayey silts; (2) Angular lithified cm-scale clasts (dropstones); (3) Cross-laminations, large folds and deformations; (4) Horizontal and normal graded laminations in inorganic sandy silt intervals.

(Szeroczyńska and Sarmaja-Korjonen 2007), but shields of almost all species can be recovered with the 100- μm sieve. No chemical or other physical treatments were done on the subsamples. All animal remains were picked from the same samples, and individuals were identified according to descriptions by Frey (1964), Wiederholm (1983), Rumes et al. (2005), Brooks et al. (2007), Szeroczyńska and Sarmaja-Korjonen (2007), and Luoto (2009).

Statistical analysis

Similarity percentage analysis (SIMPER) using Bray–Curtis similarity/dissimilarity measure (multiplied by 100) was done on relative taxon abundances to indicate the divergence between the intervals and the taxa primarily responsible for the community changes between intervals (Clarke 1993). The Bray–Curtis similarity measure is implicit to SIMPER. The

overall average dissimilarity was computed using all taxa, whereas taxon-specific dissimilarities were computed for each taxon individually. The SIMPER analysis was done with the program PAST (Hammer et al. 2001). Principal components analysis (PCA) was used to summarize the main directions of variation in the chironomid assemblage data in the core. The sample scores were calculated from relative abundances and \sqrt{x} -transformation of the chironomid data using the program CANOCO (version 4.52; ter Braak 2003).

Results

Ninety-five of the 124 sediment subsamples that were sieved contained remains of macro-organisms, for a total of 1263 fossil individuals (average of ~13 individuals [ind]/sample) that belonged to 10 different taxa. In general, the fossil remains were worn and fragmented, probably because of the minerogenic nature of the sediment. The number of individuals was highest in intervals Ia (629) and IIIb (538) and lowest in interval Ib (96). In interval IIIb, the wet sediment subsamples of 1.0 to 6.0 g (mean = 2.8 g) contained 0 to 67 individuals (mean = 20), in interval Ib subsamples of 1.0 to 5.2 g (mean = 2.7 g) contained 0 to 20 individuals (mean = 3.4), and in interval Ia subsamples of 0.7 to 5.9 g (mean = 3.0 g) contained 0 to 125 individuals (mean = 23.4). Only one sample at the base of the core contained <1 g of wet sediment because of lack of sediment material. One individual was encountered in this sample.

Most remains belonged to Cladocera (73.2%), but Chironomidae were common (26.5%). Other fossil groups encountered included oribatid mites (Arachnida:Acariformes:Oribatida) (0.2%) and mayflies (Insecta:Pterygota:Ephemeroptera) (0.2%) with single individuals in the samples where they occurred. Of the 2 cladoceran taxa, *Chydorus sphaericus*-type (55.1% of all remains) was more abundant than *Bosmina (Eubosmina) longispina*-type (18%), whereas for the chironomids, *Heterotrissocladius subpilosus*-type (19.3%) was the most abundant taxon followed by *Protanypus* (4.3%). Photographs of the taxa encountered are shown in Fig. 3A–J.

Interval IIIb was dominated by *C. sphaericus*-type and *B. longispina*-type, whereas all other taxa were rare (Fig. 4). In general, *C. sphaericus*-type was the dominant cladoceran (Fig. 5). Within interval Ib, *B. longispina*-type disappeared and *C. sphaericus*-type became less abundant, whereas *H. subpilosus*-type and *Protanypus* increased slightly. Interval Ia was dominated by *C. sphaericus*-type, and *H. subpilosus*-type was also common (Figs 4, 5).

The SIMPER analysis showed overall average faunal dissimilarity of 86.3 (Bray–Curtis) between

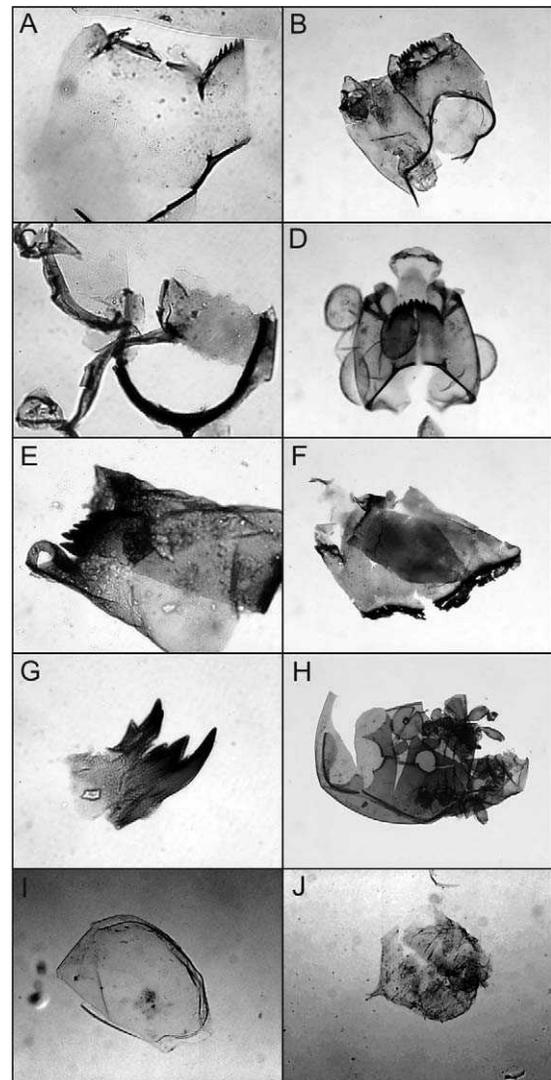


FIG. 3. Fossil invertebrate taxa encountered from the sediment profile of Pingualuit Crater Lake. A.—*Oliveridia tricornis*-type split head capsule. B.—*Micropsectra radialis*-type head capsule. C.—*Protanypus* split head capsule. D.—*Heterotrissocladius subpilosus*-type head capsule. E.—*Pseudodiamesa arctica*-type split head capsule. F.—*Parochlus kiefferi*-type split head capsule. G.—Ephemeroptera mandible. H.—Liacaridae/Astegistidae cuticle. I.—*Chydorus sphaericus*-type shield. J.—*Bosmina (Eubosmina) longispina*-type shield.

intervals IIIb and Ib and dissimilarity of 71.3 between intervals Ib and Ia (Fig. 4). The individual contribution of *C. sphaericus*-type between intervals IIIb and Ib was 39.3 (45.5%), whereas *B. longispina*-type contributed 27.4 (31.8%), *H. subpilosus*-type contributed 10.2 (11.8%), and *Protanypus* contributed 6.8 (8%). The contribution to dissimilarity between intervals Ib and Ia was attributed to *C. sphaericus*-type with 37.1 (52.2%), *H. subpilosus*-type with 20.1 (28.3%), and *Protanypus* with 8.5 (12%). PCA axis 1 explained

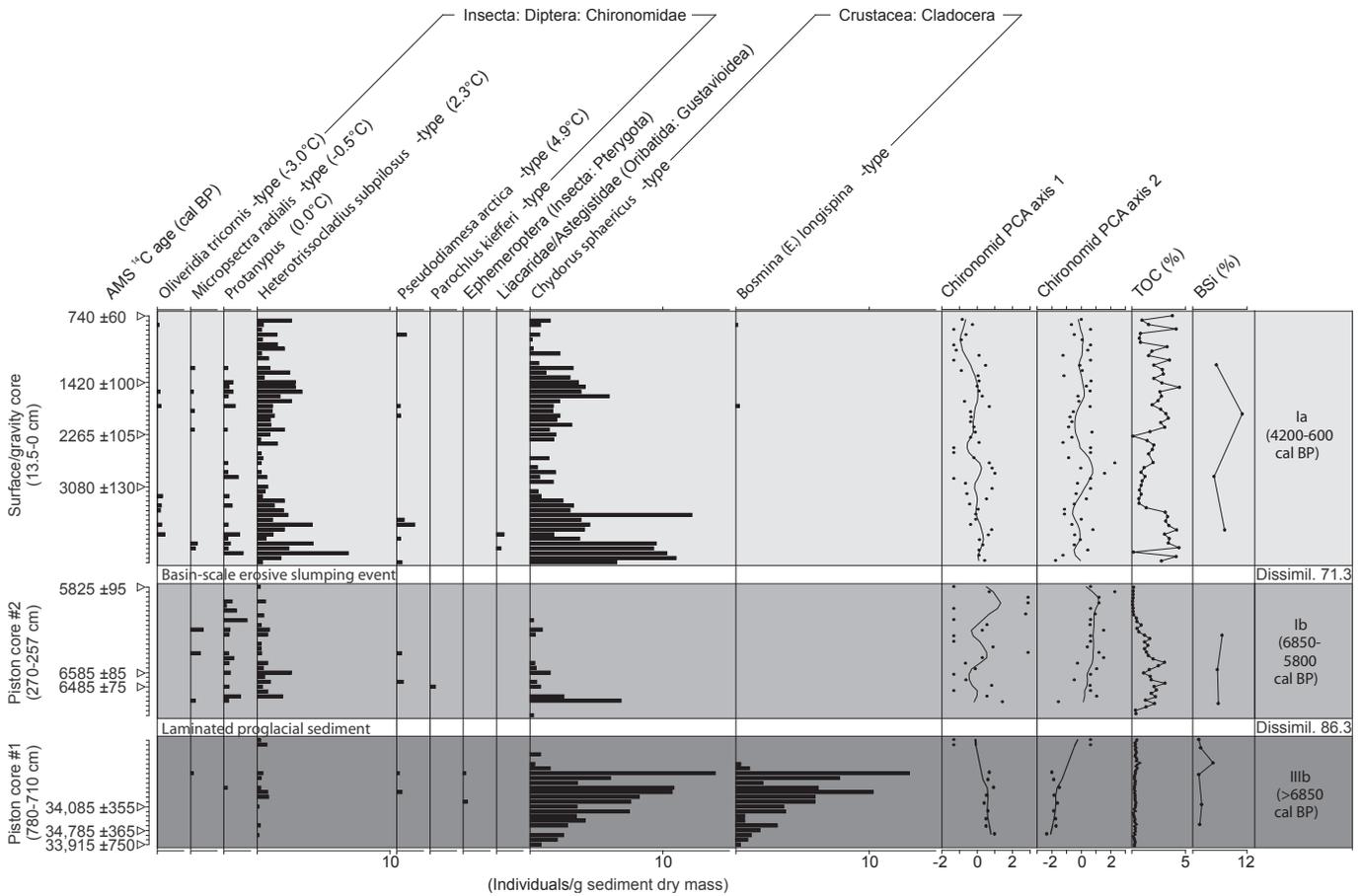


FIG. 4. Invertebrate stratigraphy of Pingualuit Crater Lake within the organic-rich intervals IIIb, Ib, and Ia expressed as absolute abundances, principal components analysis (PCA) scores for chironomids, and % total organic C (TOC) and biogenic silica (BSi). The organic intervals are disrupted by laminated proglacial sediments and a basin-scale erosive slumping event. The chronology is based on pretreated accelerator mass spectrometry (AMS) ¹⁴C bulk dates (see Guyard et al. 2011), whereas the nontreated bulk samples were excluded. The chironomid taxa are arranged according to their temperature optimum (in brackets) in lakes of northern Québec (Larocque et al. 2006) and the faunal dissimilarity between the intervals is based on similarities percentage (SIMPER) analysis. TOC and BSi data were published by Guyard et al. (2011). cal BP = calibrated years before present.

57.8% of the total variance in the chironomid data, whereas the variance explained by axis 2 was 24%. Interval IIIb had generally high PCA-axis-1 and low axis-2 scores. Interval Ib had large variability in the axis-1 scores, but the axis-2 scores were persistently high. Interval Ia was characterized by low axis-1 and intermediate axis-2 scores.

Discussion

Chronological interpretation

The lowermost interval (IV) of the sediment core from Pingualuit Crater Lake was formed by very dense diamicton, which reflects a subglacial basal melt-out environment and marks the end of subglacial conditions at the lake (Fig. 2; Guyard et al. 2011). According to Guyard et al. (2011), the subsequent

organic-rich interval IIIb probably represents an initial stage of the Holocene with a strong proglacial influence and floating ice blocks. The deposition of finer-grained and faintly laminated sediments probably reflects a turbulent glacial sediment flow that was related to the melting of the ice sheet in the crater catchment (HG, P. Francus, GS-O, RP, and SH, unpublished data). Black et al. (2012) argued that the section IIIb (DR3 in their paper) may have accumulated before the Holocene deglacial ages, an interpretation that is supported by the ¹⁴C dates reported by Guyard et al. (2011). The unique nature of the diatom flora and invertebrate fauna (shown by the SIMPER analysis) in interval IIIb relative to the later intervals, together with the dating results, which indicate a mid-Wisconsinan, late Marine Isotopic Stage 3 (MIS3) age, may reflect a period of temporarily ice-free

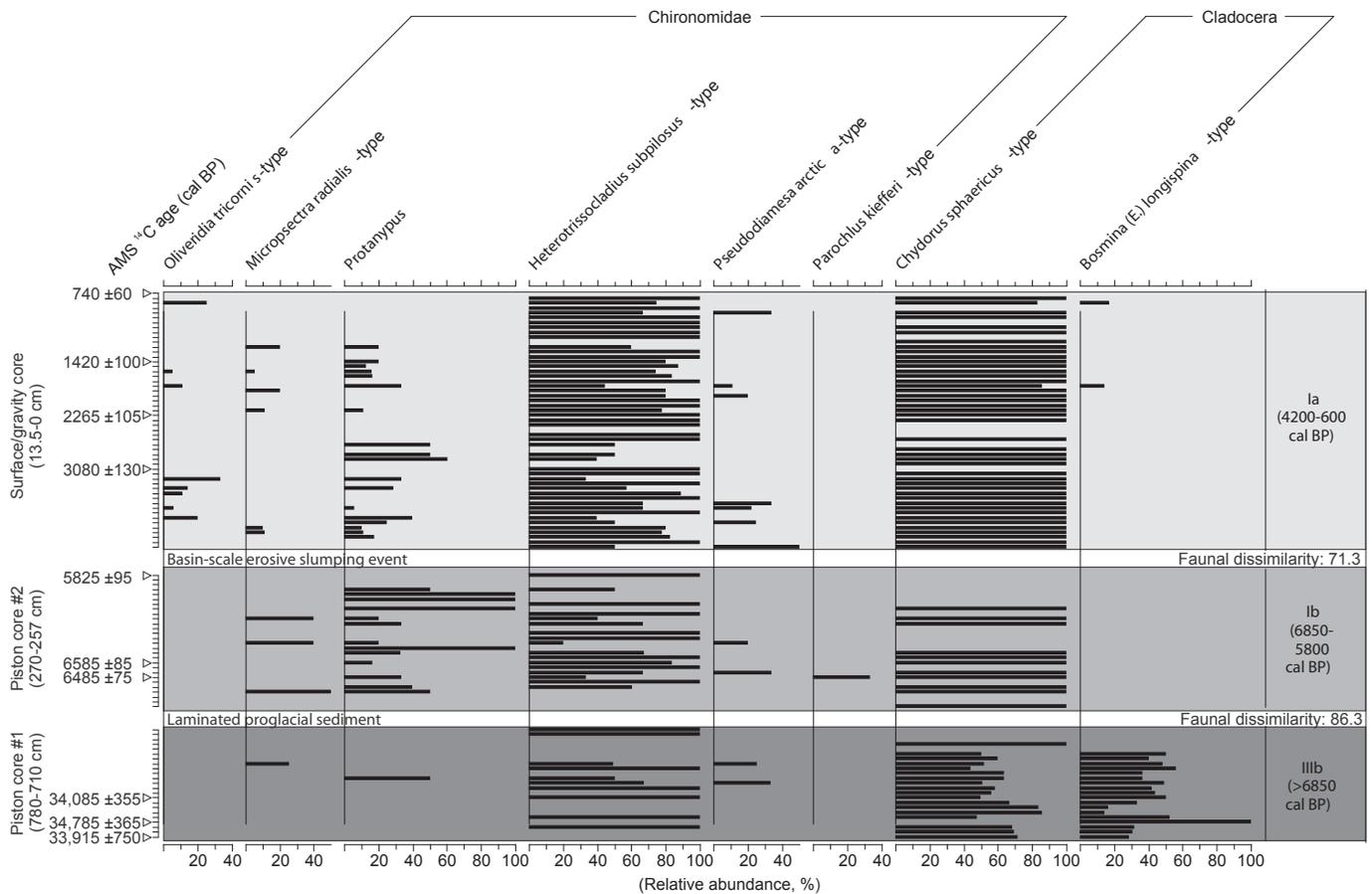


FIG. 5. Relative Chironomidae and Cladocera abundances in the sediment profile from Pingualuit Crater Lake. The organic intervals are disrupted by laminated proglacial sediments and a basin-scale erosive slumping event. The chronology is based on pretreated accelerator mass spectrometry (AMS) ¹⁴C bulk dates (see Guyard et al. 2011), whereas the nontreated bulk samples were excluded. The chironomid taxa are arranged according to their temperature optimum (from coldest to warmest) in lakes of northern Québec (Larocque et al. 2006). The faunal dissimilarity between the intervals is based on similarities percentage (SIMPER) analysis. cal BP = calibrated years before present.

conditions during the late Pleistocene. This conclusion would be in agreement with the combined evidence presented by Klemm et al. (2010) proposing only limited residual ice cover on the Ungava Peninsula during the mid-Wisconsinan interstadial (MIS3). Partial deglaciation of the Hudson Strait area (Fig. 1) during MIS3 also was suggested by Andrews and MacLean (2003), and ice-free conditions apparently also prevailed within the central parts of the Scandinavian Ice Sheet (Helmens and Engels 2010, Johansson et al. 2011). However, an Infra-Red Stimulated Luminescence (IRSL) date from interval IIIb reflects sediment buried without proper bleaching, consistent with a till or waterlaid deposit (Guyard et al. 2011), whereas the ¹⁴C dates potentially reflect a mixing age. Furthermore, detailed microsedimentological characterization indicates a

large range of glacial microstructures confirming the presence of an ice-sheet and its influence on sedimentation processes within facies IIIb (HG, P. Francus, GS-O, RP, and SH, unpublished data). Therefore, the precise chronological interpretation of the interval remains to be solved, but we advance as the most likely scenario the early Holocene with prevalence of proglacial conditions. The chronologies of sections Ib and Ia are better defined, though disconnected by an apparent slump event (mass wasting deposit) (Guyard et al. 2011). Increased total organic C (TOC) and BSi (Fig. 4; Guyard et al. 2011), lacustrine productivity bloom of diatoms (Black et al. 2012), and the presence of benthic animals (Fig. 4) provide combined evidence for the absence of a permanent ice cover during intervals IIIb, Ib, and Ia.

Interval IIIb (>6850 cal BP): the proglacial environment

Despite the glacial sediment deposition, temporarily ice-free conditions at Pingualuit Crater Lake during interval IIIb are indicated by the presence of planktonic diatoms including the endemic and presently extinct *Cyclotella pingualuitii* (Black et al. 2012). These ice-free conditions also are supported by our data. For example, the only planktonic animal in our record, the cladoceran *B. longispina*-type, was the most abundant taxon in section IIIb, together with a littoral/benthic *C. sphaericus*-type (Figs 4, 5). Under extreme conditions, *C. sphaericus*-type also can occur among the plankton (Lennon et al. 2003) where it grazes small algae in suspension (de Eyto and Irvine 2001). Pingualuit Crater Lake has an extremely limited littoral zone because of its steep basin walls and boulder-strewn slopes, so it is likely that *C. sphaericus*-type has survived in the lake by feeding on planktonic algae. The diatom record from Pingualuit Crater Lake provides evidence for planktonic diatom production during interval IIIb (Black et al. 2012) that allowed the proliferation of the *B. longispina*-type/*C. sphaericus*-type community. Because *B. longispina*-type was abundant only in interval IIIb, it is possible that this period was more productive than the following intervals. The increase in productivity could be a result of higher nutrient inputs released by the melting ice sheet (cf. Luoto et al. 2012). When the lake became ice free, the increase in nutrient availability may have caused this small bloom of planktonic aquatic biota. Guyard et al. (2011) proposed low primary production during interval IIIb, based on the very low contents of TOC and BSi (see also Fig. 4), but this combination could result simply from redeposition of glacial material that was mixed with organic sediments.

In general, the chironomid taxa encountered in the sediments of Pingualuit Crater Lake were rather typical for lakes in northern Québec (Larocque et al. 2006, Saulnier-Talbot and Pienitz 2010) and adjacent Baffin Island (Fig. 1; Francis et al. 2006, Axford et al. 2009b) including characteristic cold-adapted profundal chironomids (Walker 1990, Barley et al. 2006). Chironomids respond mainly to prevailing thermal conditions (in particular the egg, larval, and pupal stages respond to water temperature and the adult stage responds to air temperature), so in sedimentary records, the main direction of variance in fossil chironomid assemblages is expected to be temperature driven (Brooks 2006, Walker and Cwynar 2006, Eggermont and Heiri 2012). Summer temperature also can affect chironomid assemblages in deep lakes in ways that are not related to its covariation with

trophic state (Verbruggen et al. 2011). Therefore, the primary ordination (PCA) axis scores for chironomids, which explained 58% of the total variance, are assumed to reflect the temperature development, as has been found in many previous multiproxy studies including chironomids (Luoto et al. 2009, Hausmann et al. 2011, Medeiros et al. 2012).

The only chironomid taxon with more than sporadic occurrence in interval IIIb was *H. subpilosus*-type, which has a wider temperature optimum in lakes of northwestern Québec than most other core taxa (Larocque et al. 2006; Fig. 4). Regardless of the chronological interpretation, its presence indicates relatively warm climatic conditions at the time of accumulation. Interval IIIb also was characterized by high chironomid PCA-axis-1 scores (Fig. 4), which probably reflect the positive relationship between PCA scores and temperature in the sediment record. The present-day distribution of *H. subpilosus*-type in northwestern Québec is restricted to forest-tundra and tundra lakes (Larocque et al. 2006). Although *H. subpilosus* is considered a strongly cold-stenothermic species characteristic of ultra-oligotrophic lakes (Sæther 1975, Coffman et al. 1986), it can occur in relatively warm boreal lakes as a glacial relict in the cold profundal zone of large and deep lakes (Brundin 1949, Meriläinen et al. 2001). In addition, the occurrence of mayflies in this interval, although with single individuals/sample (3–4 g wet sediment), may reflect warmer conditions because they are often absent from tundra sites and more abundant in forest lakes in northern Europe (Luoto 2009). In North America, mayflies are absent from the High Arctic but present in the tundra zone, with increasing abundance in the boreal forest zone (Danks 1981). If, according to the ¹⁴C dates and in contrast to our hypothesis, interval IIIb does indeed reflect interstadial (MIS3) conditions, the interpretation of a warmer climate would be in agreement with the results of Francis et al. (2006) who showed that interstadial temperatures were warmer than at any time during the Holocene interglacial.

Interval Ib (~6850–5800 cal BP): the postglacial environment

At the time of deposition of sediments corresponding to interval IIIb, Pingualuit Crater Lake was connected to neighboring Lake Laflamme via an outlet (Bouchard et al. 1989, Guyard et al. 2011) that probably enabled fish, specifically Arctic char (*Salvelinus alpinus* L.), to migrate into the lake. The diet of Arctic char includes mainly chironomids and zooplankton (Jørgensen and Klemetsen 2006). Thus, it has

the potential to influence the structure of invertebrate communities significantly, especially the abundance of *B. longispina*-type. The paleo-shoreline was probably lower during intervals Ib and Ia than in interval IIIb so that the outlet to Lake Laflamme would have been disconnected (Guyard et al. 2011). The isolation of Pingualuit Crater Lake and its Arctic char population would have resulted in the extirpation of *B. longispina*-type (Fig. 4) through more efficient feeding under diminished food availability. However, we found no fossil fish scales in the sediment core that could have provided evidence for the presence and abundance of Arctic char. The disappearance of *B. longispina*-type also could be related partly to decreased nutrient and food availability or climate-related factors.

Black et al. (2012) described a newly discovered diatom species *Cyclotella pingualuitii*, which disappeared from the fossil record in a manner similar to the disappearance of *B. longispina*-type from the invertebrate record after interval IIIb (Figs 4, 5), and speculated that its extinction may have implications for determining regional climatic-forcing mechanisms. In addition to the extirpation of *B. longispina*-type following interval IIIb, *C. sphaericus*-type markedly decreased in interval Ib, which corresponds to the early postglacial period (~6850–5800 cal BP; Fig. 2) and marks the transition from proglacial to postglacial conditions during the Holocene Thermal Maximum (HTM). Northern lakes usually are dominated by *C. sphaericus*, whereas *Bosmina* usually is the most abundant species in warmer lakes (Frey 1964). These distributional patterns suggest that interval IIIb was warmer than the later organic intervals. The SIMPER analysis showed that the species divergence between intervals IIIb and Ib was more significant than between intervals Ib and Ia, suggesting that interval IIIb was the most distinct, whereas intervals Ib and Ia were more similar.

Of the chironomids, *H. subpilosus*-type continued to persist as the most abundant taxon in interval Ib, whereas *Protanypus* (Oliver 1986), which has a lower temperature optimum than *H. subpilosus*-type in northwestern Québec (Larocque et al. 2006), became more common (Figs 4, 5). However, multiproxy paleolimnological reconstructions from a tundra lake on the eastern coast of Ungava Bay indicate cold early postglacial conditions (interval IIIb in our record) followed by a warming trend initiated at ~6400 cal BP (interval Ib in our record) (Fallu et al. 2005). Total invertebrate productivity was much lower in interval Ib than in intervals IIIb and Ia (Fig. 4). Nutrient availability may have decreased because of reduced glacial inputs following the retreat of the ice sheet

from the catchment and could have partly caused the community shift. However, the proportion of BSi was higher in section Ib than in IIIb (Fig. 4) indicating an opposite productivity trend for siliceous algae. A closer look at the decreased invertebrate productivity reveals that it was a result of the decline of Cladocera, whereas chironomid productivity increased similarly in accordance with the BSi data (Fig. 4). Chironomids probably respond mainly to temperature in our record (PCA-axis-1 scores), but the chironomid PCA-axis-2 scores may reflect the secondary influence of nutrient (food) availability because it shows correspondence to the increased BSi and TOC concentrations (Fig. 4). This explanation would suggest that climatic conditions were more variable, but lake productivity increased in interval Ib compared to interval IIIb.

Interval Ia (~4200–600 cal BP): late Holocene

Intervals Ib and Ia were interrupted by a mass wasting deposit (basin-scale erosive slide) possibly associated with slope instability (rapid discharge events) or an earthquake (seismic activity caused by rapid glacio-isostatic rebound) that would have triggered the rotational slide ~4200 cal BP (Guyard et al. 2011). Based on the invertebrate record, interval Ia (corresponding to the late Holocene; ~4200–600 cal BP) appears to have been more favorable than Ib because the total number of chironomid individuals encountered was much higher. In addition, cladoceran productivity increased significantly even though *B. longispina*-type remained absent (disregarding the 2 sporadic occurrences) (Fig. 4). The absence of *B. longispina*-type, which is sensitive to fish predation (Jakobsen and Johnsen 1988), could reflect the presence of Arctic char that would have prevented its successful recolonization.

The same taxa as in interval Ib continued to dominate the chironomid and cladoceran communities, including *C. sphaericus*-type, *H. subpilosus*-type, and *Protanypus* (Fig. 5). The appearance of the cryophilic chironomid *Oliveridia tricornis*-type, a taxon characteristic of ultra-oligotrophic lakes (Coffman et al. 1986) and with the lowest temperature optimum among the core taxa (Larocque et al. 2006; Fig. 4), contrasts with increased invertebrate productivity that indicates more favorable climatic conditions. In addition to invertebrate productivity, the BSi and especially TOC concentrations were high compared to the previous intervals. These changes corresponded well with the increased chironomid PCA-axis-2 scores, which also reflect slightly increased nutrient availability (Fig. 4). However, the success of *O.*

tricornis-type indicates that this interval was cooler than previous intervals, although the abundance of *O. tricornis*-type was too low to serve independently as reliable evidence. Stronger evidence for colder temperatures in interval Ia is provided by the chironomid PCA-axis-1 scores that showed a trend toward more negative (colder) values toward the top of the sediment profile. In general, our record supports the notion that profundal chironomids also respond to climate change in extremely deep lakes. Similar evidence for climate sensitivity of deep profundal taxa was reported from Lake Silvaplana (77 m) in Switzerland (Larocque et al. 2009).

In contrast to the indication that the presence of *O. tricornis*-type represents Neoglacial climatic cooling, the occurrence of oribatid remains in the late Holocene record suggests warmer conditions. Liacaridae and Astegistidae are present in North America only in low Arctic sites (i.e., tundra) including Nunavik, and they are absent from the Canadian High Arctic (Danks 1981). However, oribatids were encountered within sediments of the very early part of the sequence (~4000 cal BP), so the climate may have cooled towards the end of interval Ia, as also indicated by the decreasing chironomid PCA-axis-1 scores in the interval. Late Holocene cooling may also be inferred based on the decrease of total invertebrate abundance from the lower to the upper part of the interval (Fig. 4). Such regional cooling was suggested based on palynological records that revealed expansion of tundra vegetation in the subarctic Labrador–Ungava region (Short and Nichols 1977). In addition, chironomid-inferred water temperatures from lakes in Baffin Island suggest cooler temperatures for the past 4000 y (Axford et al. 2009a, b), concurrent with the increase of *O. tricornis*-type in our record.

Conclusions

The fossil invertebrate record from Pingualuit Crater Lake revealed distinct faunal assemblages in the 3 separate fine-grained and relatively organic-rich sediment intervals. The most prominent feature was the success of *B. longispina*-type in interval IIIb (before ~6850 cal BP), representing proglacial conditions, and its subsequent extirpation. The disappearance of *B. longispina*-type probably was related to the hydrological isolation of the basin following interval IIIb and the associated isolation of its Arctic char population, which then preyed more efficiently on the planktonic invertebrates. The interval Ib showed slightly increased chironomid productivity compared to interval IIIb, but cladoceran productivity decreased markedly. Interval Ib (~6850–5800 cal BP) corresponds to

the transition between proglacial and postglacial conditions during the HTM, and our records suggest that generally warmer climatic conditions prevailed compared to those during interval IIIb, although with higher variability as suggested by the chironomid PCA-axis-1 scores. The appearance of *O. tricornis*-type in the stratigraphy of interval Ia (~4200–600 cal BP) and the progressively decreasing chironomid PCA-axis-1 scores probably reflect the general Neoglacial cooling climate trend documented for the Ungava Peninsula during the late Holocene, although lake productivity probably increased slightly, as suggested by the increased chironomid PCA-axis-2 scores, BSi, and TOC data.

Our long-term paleoecological archives can be considered as a significant testimony to the resilience of aquatic animals under extreme environmental conditions in the extremely dilute and ultra-oligotrophic waters of this very deep Arctic crater lake basin. The dynamics of chironomid fauna in Pingualuit Crater Lake appear to have been driven by climate changes, whereas the cladoceran community shifts were probably more related to biotic factors, such as predation. Moreover, our results provide new insights into the postglacial history of the Ungava area, with a stationary ice front in the initial stages of the Holocene, favorable climatic conditions during the mid-Holocene, and a general late-Holocene cooling.

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