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AMS ^{14}C dating of tundra lake sediments using chironomid head capsules

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Abstract

Radiocarbon dating of late-Quaternary sediments from high-latitude lakes is often complicated by the influx of old carbon, reservoir effects, or both. If terrestrial plant macrofossils are also absent, the dating of bulk sediment often provides the only means to establish chronologies for these problematic sediment sequences. Given that chironomid (non-biting midge) remains are sufficiently abundant in many northern lakes to be ^{14}C-dated via the accelerator mass spectrometry (AMS) method, we decided to explore their utility in age-model development. Five age determinations based on chironomid material were obtained from a lake sediment core sampled in the shrub tundra of northern Québec. These results were compared to six AMS bulk sediment ages, as well as to a date obtained from *Drepanocladus* spp. The chironomids yielded consistently younger ages (with increasing age offset upcore), confirming both the presence of a reservoir effect and the value of chironomids in establishing more reliable ^{14}C chronologies.

Introduction

Paleoenvironmental studies are essential to understand the dynamics of climate and ecosystems, and also to predict future changes in climate and ecosystems. A great number of such studies are being conducted using lake sediments. The chronologies of these reconstructions often rely on radiocarbon dating of organic matter present in bulk sediment (e.g., Gandouin and Franquet 2002; Sarmaja-Korjonen 2002) or as macrofossils (e.g., wood and plant remains, Cremer et al. 2001; wood, Ponader et al. 2002; aquatic moss and wood, Porinchu and Cwynar 2002). Even though accelerator mass spectrometry (AMS) allows samples of only a few milligrams to be dated, many problems are still encountered with the type of material dated (reviewed in Björck and Wohlfarth 2001). The most reliable materials for dating are terrestrial plant macrofossils (MacDonald et al. 1987; Snyder et al. 1994; Arnold 1995; Abbott and Stafford 1996; Child and Werner 1999; Bennike 2000) or pollen (Brown et al. 1989). However, with increasing distance from arctic and alpine treelines, organic matter becomes sparse in the catchment basin of tundra lakes and ponds. Thus, in these remote regions, where the organic matrix of lake sediments is mainly composed of humic substances or autochthonous organic matter (including algae), it is often difficult to find suitable plant macrofossils or pollen for radiocarbon dating.

In the absence of terrestrial plant macrofossils, bulk sediment is the only readily available dating material. Unfortunately, in many cases allochthonous 'old-carbon' may have entered the system, contaminating the sediment and biasing radiocarbon results. In northern Fennoscandia, the redeposition of organic material from the sparsely vegetated catchment is suggested as potentially causing abnormally old dates in basal core sediments (Seppä and Weckström 1999). The problem of dating bulk sediment was already noted in 1974 in Colour Lake, Axel Heiberg Island, where contamination by carbon-rich shale seemed to be the likely cause for anomalously old ages (Blake 1974). In northern Québec and Labrador, the problem is known from some areas where the sediments have been contaminated by organic matter derived from deposits of early or mid-Wisconsinan age (Short 1981; Allard et al. 1989; Clark et al. 1989). Following glaciation 'old carbon' may be leached or reworked from rocks, soils, and other deposits (Sutherland 1980). Early postglacial lake sediments often contain little organic matter; thus, the dating results are highly vulnerable to errors from even a small amount of contaminant (Sutherland 1980).

Abnormal results throughout a whole sequence are also common where a clear reservoir effect has been identified (MacDonald et al. 1987, 1991; Arnold 1995). In Toboggan Lake (southwestern Alberta, Canada), such an effect was either caused by the isotopic exchange between carbonate species, by the formation of CO_2 from ^{14}C-deficient bicarbonate through isotopic exchange, or by the production of CO_2 by oxidation of old organic materials (MacDonald et al. 1987, 1991; Arnold 1995). In the study of Snyder et al. (1994), abnormal ages are related to the presence of coal seams and/or to streams draining limestone terrain in the drainage basin of Linnévatnet (western Spitsbergen). Child and Werner (1999) found that bulk sediment dates from Wonder Lake (central Alaska, USA; Anderson et al. 1994) had also been affected by hard-water conditions, likely caused by the presence of carbonate-bearing bedrock or glacial drift in the lake's catchment. In Round Loch of Glenhead (Galloway, southwest Scotland), only the uppermost dates of a sequence were found to be affected by old carbon eroded from peat in the catchment (Jones et al. 1993).

The dating of terrestrial material to eliminate the influence of reservoir carbon was long perceived as the only apparent solution to the problem. However, with AMS, chitinous remains of arthropods can be dated, in addition to terrestrial plant macrofossils. The chitin of insect exoskeletons is a polysaccharide that is chemically similar and functionally equivalent to the cellulose of plants (Keeton and Gould 1993). In an early effort, chironomid (Diptera) larval head capsules were dated by Jones et al. (1993). Their four chironomid ages yielded younger results than adjacent bulk sediment samples (within 5 cm), but an inversion was present in the two most recent samples. Snyder et al. (1994) had only one age determination based on aquatic insects (dominated by chironomid remains). This date was older than those on terrestrial plant remains, but younger than most undifferentiated organic matter. Another study on a Baffin Island lake showed that isolated macrofossils and chironomid head capsules yielded much younger ages (by $\sim$10 ka) than humic acid extract dates (Wolfe et al. 2001). Child and Werner (1999) showed in an Alaskan lake that ages obtained from aquatic invertebrates (e.g., Cladocera ephippia and chironomid head capsules) and bulk sediment were similar and significantly older than ages obtained from terrestrial plant macrofossils.

Because of the contradictory and somewhat ambiguous nature of earlier results, we chose to date chironomid head capsules from the sediments of 'Lake K2', a small tundra lake in northern Québec. Lake K2 is the site of a high-resolution paleoenvironmental study where a reliable chronology is crucial. AMS dating of the aquatic moss *Drepanocladus* spp. at the base of the sedimentary sequence indicated a strong contamination by old carbon. Four results based on bulk sediment (gyttja) were subsequently added to the sequence but were not considered reliable because of the potential presence of old carbon in the watershed. In our attempt to develop a more reliable chronology, we dated five chironomid microfossil samples from the same core.

Study site

Lake K2 (informal name; 58° 44′ 05″ N, 65° 56′ 03″ W) was sampled on 17 April 1998. It is an oligotrophic lake located 6 km northeast of the town of Kangiqsualujjuaq (George River), about 11 km southeast of Ungava Bay and at 167 m above present-day sea level (asl) (Figure 1). This small lake has a surface area of 3.6 ha and a maximum measured depth of 6.6 m (including 1.4 m as ice). The measured conductivity at a depth of 1.8 m was

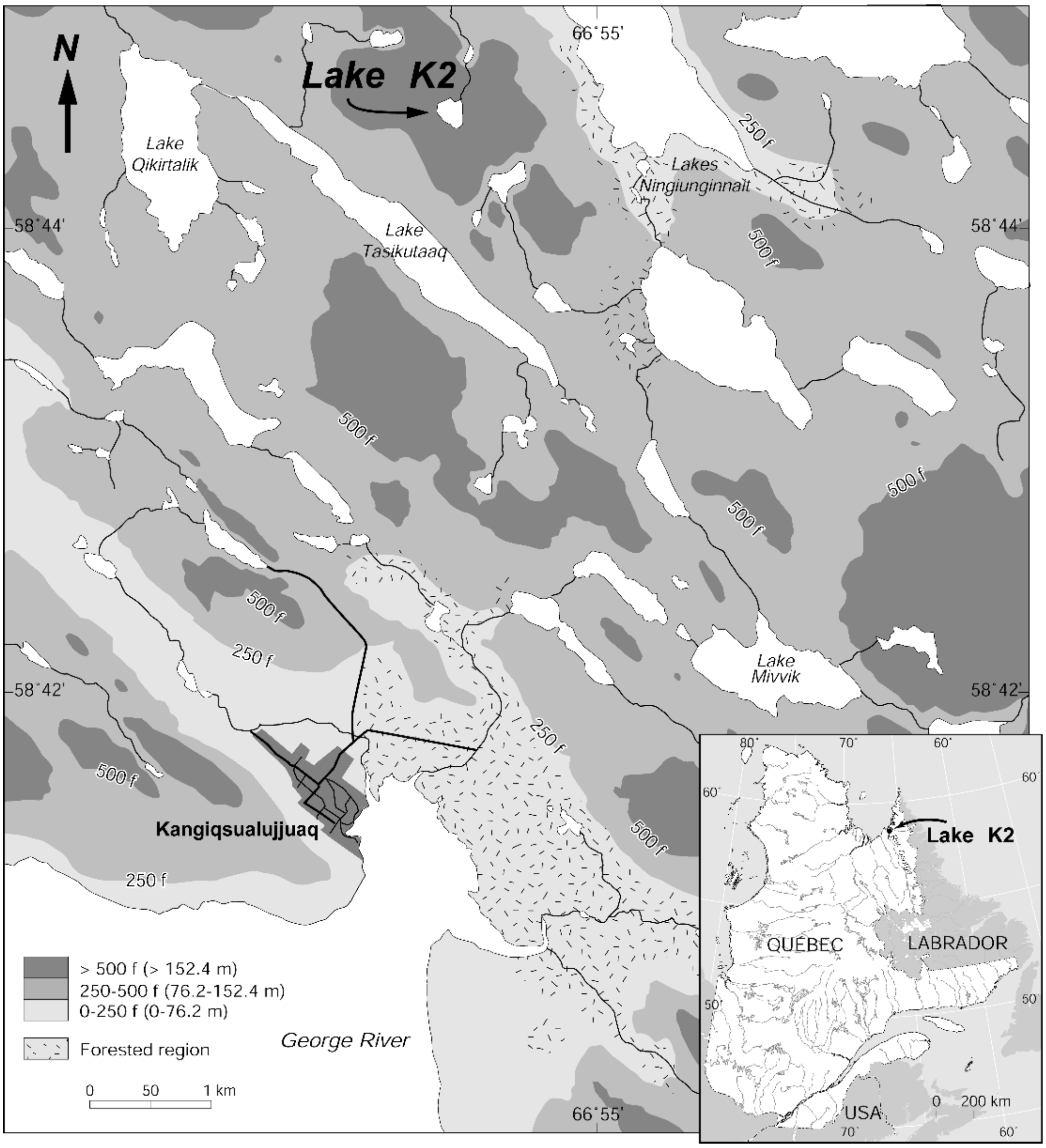

Figure 1. Location of Lake K2 near the town of Kangiqsualujjuaq in northern Québec at the shrub-tundra/forest tundra limit.

10 μS cm^{-1} and the salinity was under the detection limit for the salinity meter.

The lake is located at the edge of the Central Lake Plateau and the George River Plateau in Precambrian bedrock of the Churchill geological province (Gouvernement du Québec 1984). The bedrock is composed of granodioritic and granitic gneiss (Geological Survey of Canada 1997). The region is believed to have been deglaciated between ca. 7500 (Allard et al. 1989; Clark et al. 2000) and 8000 ^{14}C yr BP (Dyke and Prest 1987). In this region the postglacial d'Iberville Sea attained a maximum level of 100 m (±1 m) asl (Allard et al. 1989). Located at 167 m asl on top of a plateau system, and about 3 km beyond the maximum extent of the sea, Lake K2 has not been subject to any direct marine influence since the last deglaciation. In the study region the permafrost is discontinuous and widespread (Allard and Séguin 1987). The surrounding vegetation is a patchy shrub-tundra mainly composed of *Betula glandulosa* Michx., *Alnus* spp., *Picea glauca* (Moench) Voss. (krummholz), *Vaccinium vitis-idaea* L. ssp. *minus* Lodd., *Vaccinium uliginosum* L., *Ledum palustre* L. ssp. *decumbens* Ait., and *Empetrum nigrum* L. ssp. *hermaphroditum* (Hag.) Soer.

Methods

Lake K2 was sampled from the frozen surface. A 99-cm sediment core was extracted from the centre of the lake, using a 5-cm diameter modified Livingstone piston corer (Wright et al. 1984). Clay was found at the core base, suggesting that the record spans the lake's entire history, beginning with its formation following deglaciation. The core was immediately sectioned into 1-cm thick subsamples at the coring site. The sediments above the basal clay were composed of organic-rich gyttja.

The sediments were dated by accelerator mass spectrometry (AMS). Aquatic moss remains (*Drepanocladus* spp.) were found in the basal clayey sediments at 98–99-cm depth. A subsample was dried at 60 °C for 14 h and yielded 1.6 g of uncleaned moss remains. The sample was dated at IsoTrace Laboratories, University of Toronto, Ontario. Because no other macrofossils were found in the entire sediment core, dried (60 °C for 14 h) bulk sediment was dated at four additional levels which were chosen based on changes in relative abundance of chironomids and diatoms (Fallu, submitted). The sample from close to the core base was devoid of moss fragments (83–84 cm). These four samples were also dated at IsoTrace Laboratories, University of Toronto.

To assess the accuracy of the initial bulk sediment analyses, we compared them with age determinations obtained from chironomid head capsules and with further bulk sediment dates obtained from the University of Arizona. Five levels were chosen for chironomid dating: two were adjacent to bulk sediment samples, two others were split to date chironomids and bulk sediment at the same level, while the last one (93–94 cm) was close to the core base. To obtain sufficient chironomid head capsules, 1-cm samples from two adjacent levels were combined. Bulk sediment was prepared as explained above. To isolate chironomid head capsules, the samples were first soaked in 5% KOH for 10 minutes before being rinsed with distilled water. All chironomid head capsules and all remains identifiable as a part of a chironomid head capsule were hand sorted into glass vials with a cone-shaped plastic liner. Between 1309 and 2445 complete head capsules were picked for each composite sample (yielding between 0.18 and 0.37 mg of carbon for AMS dating; Table 1). Half head capsules were counted as halves, but all smaller head capsule fragments were not counted. These seven samples were sent to the Accelerator Mass Spectrometry Laboratory, University of Arizona.

Organic matter (OM) content (%) was measured by loss-on-ignition (LOI). Subsamples were analysed at 1-cm intervals throughout the core, except between 45 and 48 cm where the samples were used for radiocarbon dating. The sediments were first dried at 70 °C for 4–5 h, before the organic matter was ignited by heating the samples to 550 °C. Once this temperature was reached, the samples were left in the furnace for 20–30 min (modified from Heiri et al. 2001).

Results and discussion

Chronology

Table 1 presents the 12 AMS dates obtained, and a depth-age profile is presented in Figure 2A. Several conclusions can be drawn from the data. First, the basal age of 10 340 ^{14}C yr BP, obtained on *Drepanocladus* spp. moss fragments, is controversial and is deemed to be unreliable. In the study region, Dyke and Prest (1987) concluded from geomorphological data that deglaciation occurred between 7000 and 8000 ^{14}C yr BP. Furthermore, Allard et al. (1989) obtained three ages from a sample of marine shells on an ancient coast line (17–21.5 m asl), near Ungava Bay at Pointe Elson, ca. 13 km north of Lake K2. The results were between 7400 and 6400 ^{14}C yr BP, thereby implying that deglaciation occurred close to 7400 ^{14}C yr BP. As mentioned in the introduction, anomalously old basal core dates have been reported elsewhere. In the vicinity of Lake K2, carbonates or coal are not a concern, but it has been proposed that sediments could be contaminated by organic matter derived from older deposits and redeposited in the sparsely vegetated

Table 1. AMS radiocarbon dates from Lake K2 sediments (chironomids and bulk sediment).

Laboratory number	Depth (cm)	Material[a]	Weight before combustion (mg)	Mass of carbon run for AMS (mg)[b]	% Yield of carbon by mass after combustion	Age (years BP)[c]	$\delta^{13}C$[d]	Age[e] (cal. BP) with range	% 'Old' carbon[f]
TO-9170	12–13	Bulk sediment	915	0.50	3.8	3960 ± 60		4235 (4417) 4550	–
AA44319	19–20	Bulk sediment	535	1.37	5.0	3960 ± 60	−25	4233 (4416) 4533	29
AA43973	19–21	Chironomids (1309 hc)	*	0.33	*	1230 ± 53	−26	1052 (1172) 1274	0
TO-9171	26–27	Bulk sediment	665	0.50	3.6	4200 ± 60		4569 (4825) 4855	–
AA44320	46–47	Bulk sediment	901	1.30	5.2	4790 ± 54	−24	5449 (5491, 5500, 5585) 5613	16
AA43974	46–48	Chironomids (2445 hc)	*	0.18	*	3390 ± 61	−26	3472 (3636) 3728	0
AA47358	59–60	Chironomids (1900 hc)	*	0.30	*	4820 ± 68	−24	5449 (5589) 5661	0
TO-9172	60–61	Bulk sediment	1100	0.50	3.5	5470 ± 60		6170 (6284) 6404	8
TO-9173	83–84	Bulk sediment	1100	0.50	2.5	6140 ± 60		6861 (7004) 7163	3
AA47359	84–85	Chironomids (2020 hc)	*	0.32	*	5880 ± 170	−21	6376 (6673, 6700, 6720) 7031	0
AA47360	93–94	Chironomids (2000 hc)	*	0.37	*	5770 ± 86	−22	6399 (6553, 6563, 6564 6594, 6594, 6613, 6615) 6753	0
TO-8179	98–99	*Drepanocladus* spp.	1600	0.50	0.6	10 340 ± 70		11 888 (12 158, 12 218, 12 306) 12 432	–

[a]hc, head capsules.

[b]IsoTrace Radiocarbon Laboratory uses a standard procedure which consists of two targets of 0.250 mg of C.

[c]The ages are corrected for natural and sputtering fractionation to a base of $\delta^{13}C = -25‰$. The sample ages are quoted as uncalibrated conventional radiocarbon dates using the Libby ^{14}C meanlife of 8033 years. The errors represent a 68.3% confidence limit.

[d]$\delta^{13}C$ is not measured in the normal ^{14}C analysis at the IsoTrace Laboratories, University of Toronto, Ontario.

[e]The computer program CALIB 4.1 (Stuiver and Reimer 1993; Stuiver et al. 1998) was used to calibrate the dates (cal. BP). The samples were processed for dating by IsoTrace Laboratories, University of Toronto, Ontario (TO) and by Accelerator Mass Spectrometry Laboratory, University of Arizona (AA).

[f]The percentage of 'old' carbon was calculated with a two-component mixing model between the ages obtained from chironomids (contemporaneous ^{14}C) and the fraction of old ^{14}C constrained as dead on ^{14}C, giving an apparent bulk sediment ^{14}C activity.

*Due to concerns of high loss of datable material in transferring between containers, chironomids were not weighed before combustion. Thus without an initial weight, % yield of carbon could not be calculated.

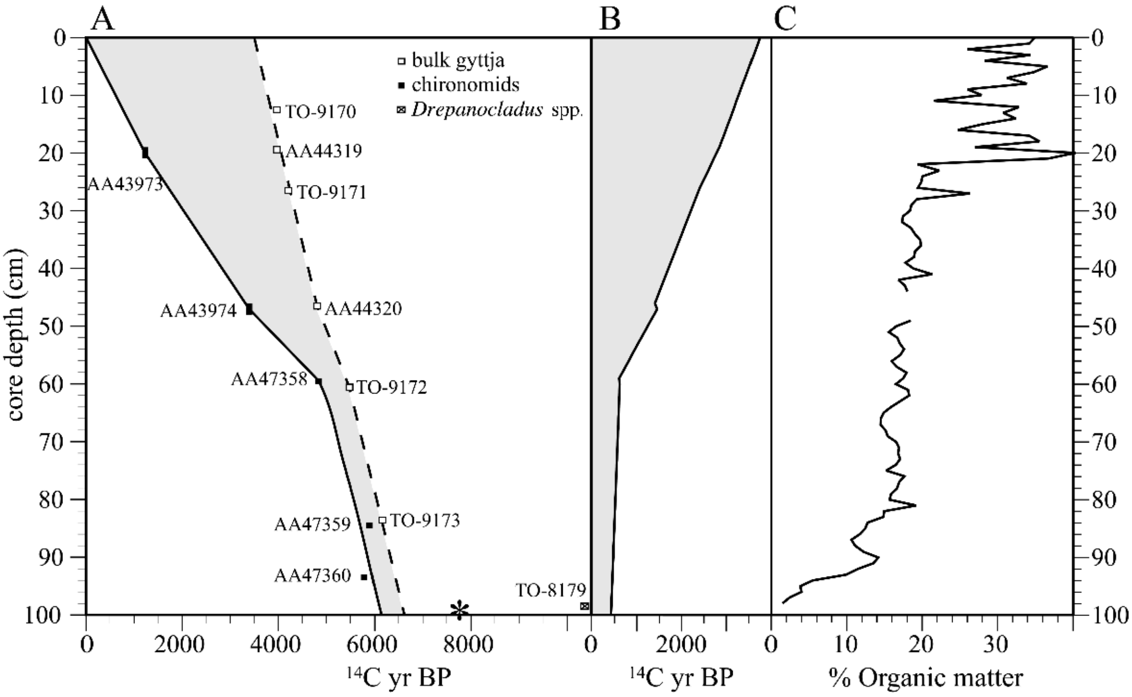

Figure 2. (A) Depth-age profile for AMS-dating in Lake K2 sediments (see Table 1 for age errors). Best estimates of true age are shown by the black line, while the dashed line shows the best estimate of bulk ages. The approximate onset of deglaciation as suggested by Allard et al. (1989), Clark et al. (2000) and Dyke and Prest (1987) is indicated by *. (B) Discrepancy between chironomid and bulk sediment ages. (C) Percent organic matter in sediments as determined by loss-on-ignition (LOI).

catchment (Short 1981; Stravers 1981; Allard et al. 1989; Clark et al. 1989). Also, although mosses have proven to yield accurate dates in arctic lakes that lack reservoir age problems (e.g., Miller et al. 1999), they can be susceptible to problems in lakes with reservoir effects, even if some species (e.g., *Drepanocladus crassicostatus*) are unable to utilize bicarbonate (Arnold 1995). In particular, MacDonald et al. (1987) noted that aquatic mosses are prone to hard-water errors in the presence of bicarbonates. As mentioned before, contamination by carbonate or coal is not a concern in Lake K2. In any case, such a small and shallow lake is well mixed and therefore should not show a ^{14}C-depleted carbon sediment–water interface, which could lead to older ^{14}C ages (Abbott and Stafford 1996).

Radiocarbon ages based on chironomid head capsules yielded significantly younger results than those based on bulk sediment (gyttja) (Figure 2A, B; Table 1). Although the bulk sediment samples were analysed in two different laboratories and may have undergone slightly different treatments, there is no apparent evidence of a systematic laboratory bias in our results. The discrepancy between ages obtained from chironomid material and from bulk sediment was not constant throughout the sedimentary sequence (Figure 2A, B). The discrepancy increased towards the core top (from only 500 years to almost 4000 years), and this indicates that it would be erroneous to subtract a constant age correction from each bulk date. The bulk sediment ages cannot be trusted. The percentage of old carbon present in the samples was calculated assuming that chironomid head capsules yield the contemporaneous age and that bulk sediment ages represent the apparent ^{14}C activity (Table 1). This shows that close to 10 times more 'old' carbon was present in the lake sediments at 19-cm depth (3%) when compared to 83-cm depth (29%).

The three bulk gyttja samples near the surface yielded very similar ages, dated at 3960, 3960, and 4200 yr BP at 12-, 19-, and 27-cm depths, respectively.

One would have anticipated a greater spread in the dating of these sediments, with the youngest date at 12 cm. Also, a minor apparent inversion is present in the two chironomid-dated samples from near the core base, but the ages are not significantly different when the error estimates are considered. The 84–85-cm sample showed the largest error in the chronology and could be less reliable.

Organic matter content is presented on Figure 2C, as measured by LOI. No evident change occurs in the organic matter content when the age discrepancy increases at about 5000 yr BP (Figure 2B), meaning that the quantity of organic matter does not seem to be responsible for these changes.

Chironomid ecology and implications for dating

Here we present some information that may help explain the origin of carbon contained in chironomid microfossils. Chironomids pass through a life cycle that includes the egg stage, four larval instars, the pupa, and the adult insect (Walker 2001). The two latter stages are usually short in duration, while the two former vary from species to species. As a larva in a lake, these organisms are found on a variety of substrata, including rocks, mud, submerged wood and aquatic plants (Pinder 1986). Although feeding has been reported to occasionally happen during the adult stage, it seems that the most important part of energy acquisition occurs during the larval stage (Tokeshi 1995). Regardless of the habitat in which they live, even morphologically close species show a high diversity of feeding modes and vary greatly in the types of food they ingest (Monakov 1972; Berg 1995). Individual species may be restricted to one feeding mode (collector-gatherers, collector-filterers, scrapers, shredders, engulfers, and piercers) or, more commonly, use several modes (Berg 1995). The mode of feeding chosen by a larva can depend on the larval size, the larval instar, food quality, sediment composition, or competition with other taxa (Berg 1995). Unfortunately, species specific foraging has been little studied. Figure 3 shows taxa that were identified in each of the levels where ages were obtained. No drastic assemblage differences can be detected between the lowermost samples (chironomid ages close to bulk sediment ages) and the more recent samples (higher discrepancy between chironomid ages and bulk sediment ages), suggesting that the predominant modes or sources of feeding have not changed and are not the cause for the discrepancy.

Chironomids have been reported to feed on five categories of food: algae, detritus and associated microorganisms, macrophytes, woody debris and invertebrates (Berg 1995). In the case of our study, macrophytes and woody debris are not discussed, because they have not been found in the sediments (except for mosses found in the basal samples, but chironomids were not used for dating these levels). Other invertebrates are not discussed because they would likely feed on the same material and thus not affect the origin of the initial carbon uptake. In general, detritus is the most frequently recorded material in chironomid guts (e.g., Monakov 1972; Baker and McLachlan 1979; Johannsson 1980; Moore 1980; Pinder 1986). In this case, detritus is defined as 'all non-living particulate organic matter and associated non-photosynthetic microorganisms' (Berg 1995). In oligotrophic lakes, Goedkoop and Johnson (1992) found that chironomids will obtain up to 47% of their carbon needs from bacteria present in the detritus. The carbon present in detritus should be from the decomposition of all organisms in the lake and catchment basin, so it originates from the CO_2 present in both the lake and atmosphere.

The second most frequent source of food is algae. Diatoms are the most common taxa ingested by chironomids (Berg 1995). In oligotrophic lakes, chironomids cannot feed as much on algae as in other environments because of the rapid degradation of the phytoplankton (Goedkoop and Johnson 1992). Algae are assumed to be in isotopic equilibrium with the CO_2 present in the lake (Abbott and Stafford 1996).

Normally, most of the CO_2 in lakes is of atmospheric origin, although some CO_2 is produced *in situ* by respiration, mostly in the sediments (Horne and Goldman 1994). Stomata allow terrestrial, emergent and floating-leaved plants to access and be in constant equilibrium with the proportion of ^{14}C present in the atmosphere (Arnold 1995). However, in a lake with an evident reservoir effect, CO_2 production by oxidation of old organic material occurs.

Recently, it was proposed by Grey (2002) that methanotrophy might be the cause of the greatly

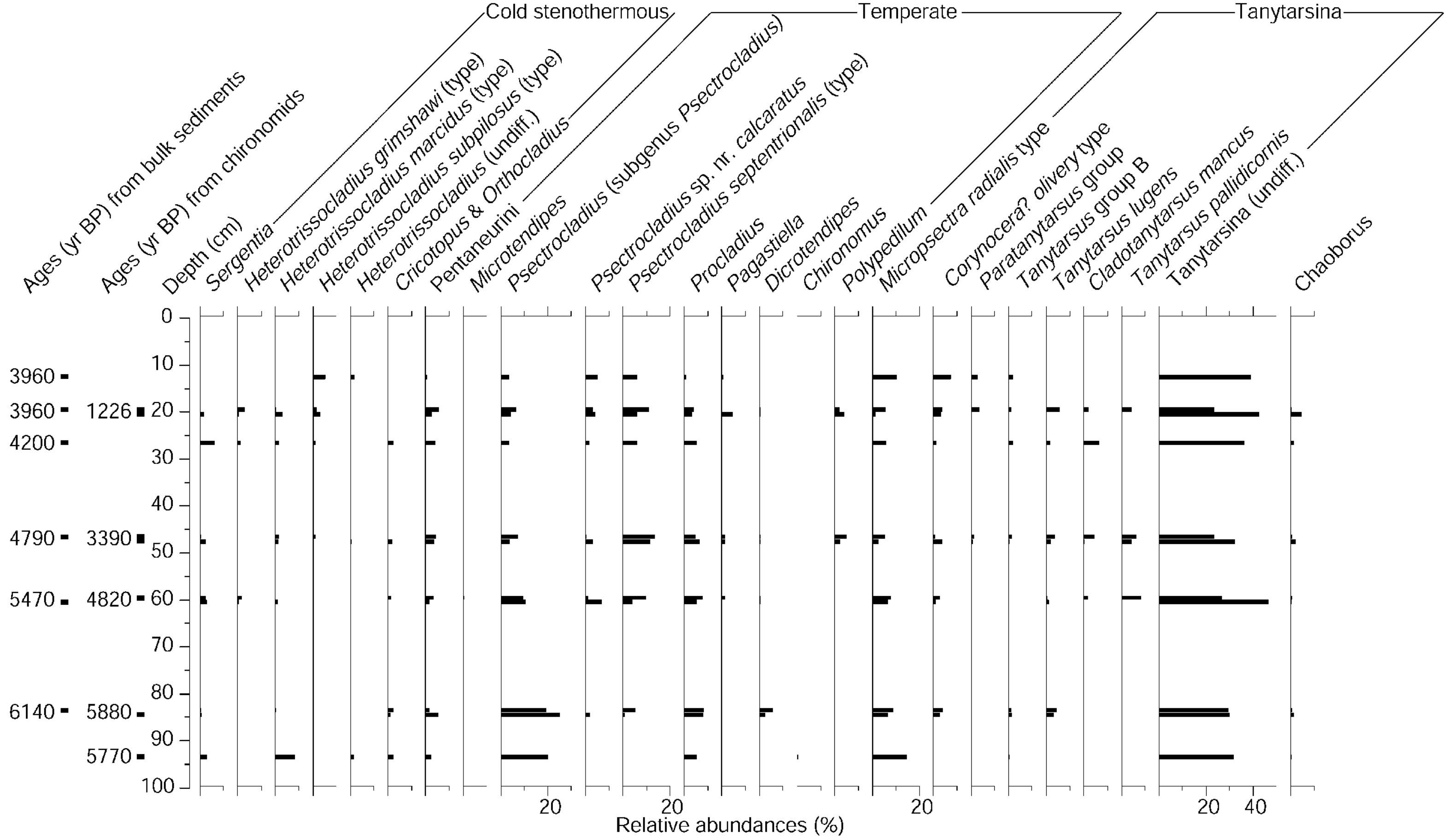

Figure 3. Chironomid assemblages in all ^{14}C AMS levels where ages were obtained.

^{13}C-depleted signature of chironomid tissues in two British lakes, meaning that chironomids were sourcing a high proportion of their body carbon from methane through microbial activity. However, both of the lakes studied by Grey (2002) are larger, deeper lakes than Lake K2 with high organic loading. These conditions create an environment more favourable for methanogenesis and methanotrophy than exists in the unstratified, oligotrophic basin of Lake K2. None of the $\delta^{13}C$ values obtained from Lake K2 midges (Table 1) are as greatly ^{13}C depleted as those reported by Grey (2002).

Proposed hypotheses explaining discrepancy among dates at lake K2

To account for the AMS dating results we have obtained from Lake K2, we propose three hypotheses:

Hypothesis #1: there is no 'hardwater reservoir effect'

As mentioned before, the absence of carbonates in Lake K2 or its catchment, the extremely low conductivity (below detection limit), the physical characteristics of the lake (small and shallow, thus well mixed), and probably a short water residence time, create conditions where no appreciable 'hardwater reservoir effect' is likely to exist.

Hypothesis #2: 'old organic carbon' is entering the lake'

The increasingly anomalous ages of the bulk sediments toward the surface could originate from a pool of refractory fossil organic carbon that gradually accumulated in catchment soils and peats throughout the postglacial period, yielding a progressively larger supply of old, erodible matter to be subsequently transported into the lake.

The old basal moss date could be contaminated by dissolved carbon from nearby older organic deposits (e.g., from early or mid-Wisconsinan deposits) washed into the lake, as proposed by numerous authors (Short 1981; Stravers 1981; Allard et al. 1989; Clark et al. 1989), and be somewhat independent from the other 'old carbon' issue.

Hypothesis #3: chironomids do not feed on the 'old carbon'

When the dates obtained from bulk sediment are compared with those obtained from chironomids, in all cases the latter yielded younger dates than bulk sediment. This suggests that chironomids are less influenced by old carbon present in the system or ingest less of it. We hypothesize that chironomids feed on organisms (algae) or detritus (mainly bacteria) that contain less 'old carbon' than bulk sediment, thus yielding dates closer to the true age of sediment deposition. This could be the result, for example, of old carbon being 'locked up' in dissolved or particulate forms that either cannot be ingested by chironomid larvae or are not easily assimilated by bacteria. Ancient soil matter, for example, may consist of indigestible refractory organic materials that pass unaltered through the chironomid gut. We also suggest that the midges are preferentially selecting fresh high quality food sources derived from both aquatic and terrestrial producers, and make little use of the refractory old organic matter (e.g., humic substances), that persists in catchment soils and sediments.

When compared with previous studies using chironomid head capsules as dating material, these hypotheses seem to be in accordance with Jones et al. (1993), Snyder et al. (1994) and Wolfe et al. (2001), but not entirely with Child and Werner (1999). Child and Werner (1999) obtained two dates from aquatic invertebrate remains (composed principally of Cladocera ephippia and chironomid head capsules) which were similar to the bulk sediment ages in Wonder Lake. In their study, it was postulated that aquatic invertebrates would yield ages similar to bulk sediment ages because the sediment was 70–80% organic matter, composed principally of aquatic invertebrates. Unlike these authors, we only used chironomids for dating Lake K2 sediments. We assume the bulk sediment of Lake K2 must have included significant amounts of old carbon from the watershed, not utilized by the chironomids. Of course, the catchment processes around Lake K2 and Wonder Lake are likely very different.

Potential sources of error when dating chironomids

When chironomids are picked, special care must be taken to avoid transferring other organic matter into the vial. When possible, chironomid remains should be cleaned of any matter present in the head capsules. Special care was taken in this study, by pressing on the head capsules with the forceps to extract trapped matter. A tiny amount of organic matter may still have been transferred into the sample submitted for dating. This would likely cause chironomid dates to be slightly older than the remains' true age.

When bulk sediment is dated, the entire organic matter must be used, including chironomids. Since chironomids could yield younger dates, one would expect bulk sediment to yield older dates once chironomids have been removed. It therefore would be interesting to date, at the same level, chironomids, bulk sediment, and a sample of bulk sediment without chironomids.

Conclusions

We do not believe that the chironomid chronology for Lake K2 is perfect, but we do feel that in this case chironomid dates were close to the true age of sediment deposition. Chironomid remains produced significantly younger dates than the bulk sediment, demonstrating (1) the presence of washed-in old detritus in Lake K2 sediment, (2) a difference in the source of carbon between the chironomid's diet and bulk sediment, and (3) an increased upcore discrepancy between chironomid and bulk sediment dates, likely associated with the succession of vegetation and accumulated allochthonous organic matter in the lake catchment.

When lake sediments are devoid of any terrestrial remains, chironomid head capsules can be picked for AMS radiocarbon dating as an alternative to dating bulk sediment. Although the method requires a considerable investment of time and skill (~10–15 h to pick 1000 head capsules), chironomid remains may yield the most reliable dating material in high-latitude tundra lakes. In Lake K2, chironomids yielded results that are closer to reality, but it is uncertain if the dates are truly accurate (i.e., yielding the true ages of the enclosing sedimentary layers).

In order to refine the method and test its potential more rigorously, many studies could be initiated. It would be helpful to better understand the diet of northern chironomids. Perhaps those chironomids feeding mostly on terrestrial material could then be dated. As proposed by Jones et al. (1993), the dating could be done at sites with accurate temporal control, including lakes with laminated sediment records. It is important to recognize the potential of this method. If terrestrial plant remains are found and dated in remote northern lakes, it would be interesting to date chironomid remains at the same level for comparison. So far, we can only state that age determinations based on chironomid remains are better than bulk sediment at Lake K2. The method should be more thoroughly tested. Chironomid head capsules may prove to be a valuable resource for accurately dating sediments from remote tundra lakes. Such studies would also enhance our understanding of chironomid feeding behaviour and carbon flow through aquatic foodwebs.

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