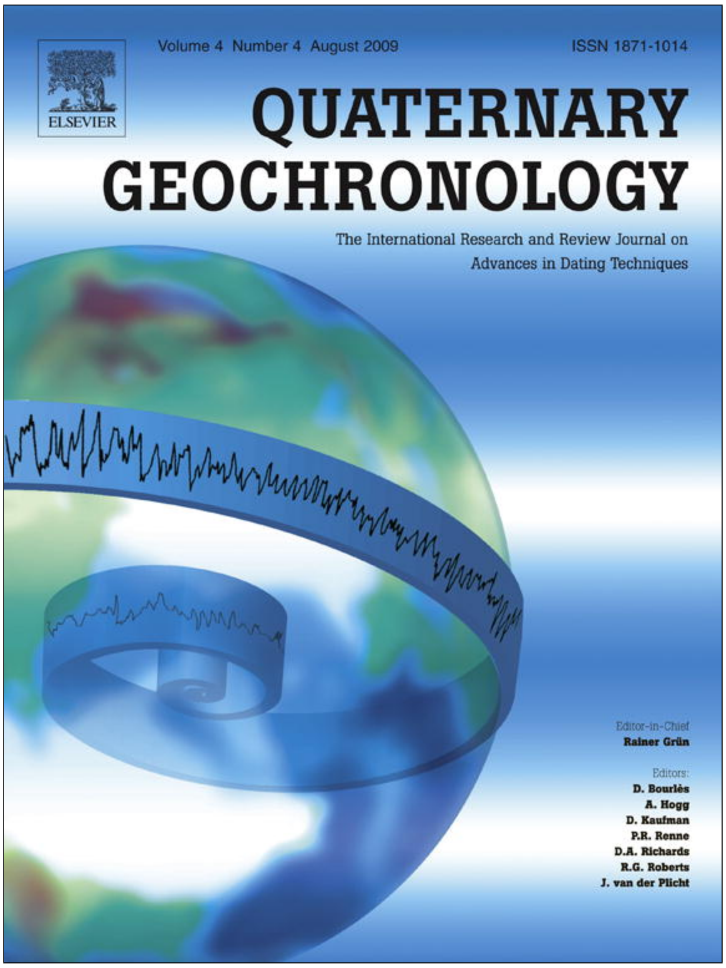

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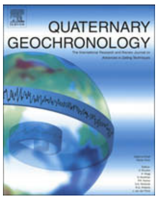

Research Paper

Establishing Holocene sediment core chronologies for northern Ungava lakes, Canada, using humic acids (AMS ^{14}C) and ^{210}Pb

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ABSTRACT

The absence of datable macrofossils in six sediment cores recovered from northern Ungava (Canada) lakes constituted a major challenge for the establishment of reliable lacustrine chronologies for the Holocene. Consequently, AMS radiocarbon dating of humic acids was used to assess age–depth in the cores. The reliability of the radiocarbon results near some of the core tops was evaluated through ^{210}Pb dating. The offset of sediment radiocarbon ages with their most probable time of formation and deposition in the lakes was found to be in the order of about 1000 years for recently deposited sediments. However, the basal dates in one core covering the entire postglacial period yielded a remarkable fit with previously established dates performed on marine shells at the maximum marine limit. Hence, the aim of this study was to describe how the two dating methods can be combined to address some of the problems paleolimnologists face when trying to assign ages to high-latitude lake sediment records. Suggestions are made for improving the quality of age–depth models developed in future studies for northernmost Québec and other comparable regions where paleolimnologists must deal with the combined challenges of very slow sediment accumulation rates in lakes, an extreme paucity of datable material and the sequestration of old carbon in the watersheds.

1. Introduction

Reconstructions of past climatic and environmental variations in the Arctic often rely on paleolimnological archives because of the abundance of lakes at high northern latitudes, and because of the advantages they offer as repositories of biogeochemical data (Pienitz et al., 2004). However, the challenges encountered in establishing accurate age control for lacustrine sediment sequences from cold environments are many-fold (e.g. Fallu et al., 2004; Wolfe et al., 2004). Foremost, due to limited terrestrial and aquatic productivity, organic accumulation rates in the arctic are low and there is often an extreme paucity of datable material preserved in the sediments. Due to the presence of permafrost, very low organic carbon turnover rates and low rates of decomposition, terrestrial organic matter can be sequestered in the watershed for prolonged periods before eventually being transported and deposited into the lake basin. This commonly leads to apparent ages that are too old (Abbott and Stafford Jr., 1996; Miller et al., 1999, 2005). Additionally, bioturbation occurs in lakes with high densities of benthic organisms that contribute to significant time averaging of the geologic record (Olsson, 1991). However, burrowing communities generally attain reduced densities in the benthos of the deepest part of high-latitude lakes, from where cores are routinely extracted, in contrast to the shallow littoral zones (e.g. Moore, 1978). Another potential difficulty may arise from the fact that some high-latitude lakes can remain perennially ice-covered during colder years, thereby creating a hiatus in sediment accumulation. On the other hand, prolonged ice cover (8–10 months per year) has the advantage of reducing or even eliminating sediment redistribution by waves and/or currents and hill slope processes (Wolfe et al., 2004).

Most of the paleolimnological studies undertaken in arctic regions have relied on radiocarbon dating of terrestrial macrofossils, bulk sediment, or both, to generate postglacial age–depth models (e.g. Michelutti et al., 2006; Seppä et al., 2003; Velle et al., 2005; Westover et al., 2006). The main problem with this procedure is the inherent error associated with depositional lag, or "redeposition", i.e. the time elapsed between the production of the

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terrestrial organic material and its deposition in the lake – lag times that can span many centuries in these cold, low productivity environments. Several factors related to the state of the catchment area's development (soils, vegetation cover, hydrology, topography, and climate) account for the magnitude of this lag time (Wolfe et al., 2004).

Even if sediments in low productivity, high-latitude lakes are dominated by allochthonous material (e.g. Lamoureux and Gilbert, 2004), there are indications that the sediments' humic acid fraction is predominantly lacustrine, i.e., autochthonous (reviewed in Wolfe et al., 2004), and therefore constitutes a viable alternative for obtaining reliable chronologies for these ecosystems. Abbott and Stafford Jr. (1996) have shown that lake sediment humic acid extracts (HA: the base-soluble, acid-precipitated fraction of organic matter) offer the potential for more reliable ^{14}C ages than do bulk sediment or most other organic matter fractions. Faced with the absence of sufficient quantities of other datable material in the cores we recovered, we decided to explore this relatively untapped method in order to further assess its reliability in the arctic context. We present a series of chronologies based on dates obtained from the HA fraction extracted from the sediments of six lakes located in northernmost Ungava Peninsula, an area with sparse paleoenvironmental data. In an effort to test the accuracy of the radiocarbon ages obtained from the HA in our cores, the data was supplemented by ^{210}Pb analyses for the recent sediments and was compared to previously published ^{14}C dates obtained from marine shells and bulk sediments in the study region. A similar procedure, in which radiocarbon dates and varve counts were supplemented with $^{137}Cs/^{210}Pb$ dating was recently successfully applied to sediments from a hard-water lake in central Germany (Enters et al., 2006). Here, we present our approach in detail and discuss its advantages and limitations in the arctic context. We also make recommendations for dating high-latitude lake sediment cores with more accuracy and precision.

2. Regional setting

The study area and its deglacial history are described in detail elsewhere (e.g. Gray, 2001; Saulnier-Talbot, 2007). Briefly, northernmost Ungava Peninsula consists of granitic gneisses of Archean and Proterozoic age, overlain with thin Quaternary tills, in which carbonate content of the matrix is $<2\%$ (Daigneault and Bouchard, 2004). The southern coast of Hudson Strait is indented by fjords and average altitudes range between 200 and 400 m above sea level (Fig. 1). Vegetation cover is sparse and consists mainly of grasses, mosses and lichens. Thousands of lakes and ponds are scattered across the area, a vast majority of which have approximately neutral pH, are oligotrophic and remain ice-covered from roughly October to the end of June. Many of the small lakes and ponds are devoid of fish and their current state of biodiversity has not been assessed. From our surface sediment surveys, we know that present-day benthic faunas include dipteran larvae and nematodes and also that siliceous protists (diatoms, chrysophytes) are abundant and diverse.

The six study lakes are located in the vicinity of the Inuit villages of Salluit, Kangiqsujuaq and Quaqtaq (Fig. 1). Different components of their sedimentary archives (fossil diatom and chironomid assemblages, LOI, biogenic silica) are described in more detail elsewhere (Saulnier-Talbot, 2007). All study lakes are head-water lakes, except for Nipingngajulik, which has a small lake draining into it. Of the other lakes, only Tasikutaaq and Allagiap Tasinga have regular inflowing streams. Table 1 provides a summary of the location and size of the lakes.

3. Materials and methods

3.1. Core collection and treatment of sediments for LOI and BSi

The cores were collected between August 2001 and May 2003 using a HTH gravity corer (internal diameter = 6.3 cm) and, in the case of Lac de l'Aéroport (AER), also with a modified Livingston piston corer to retrieve the deeper, more consolidated sediments. Cores were described and inspected to ensure that the sediment–water interface was well preserved during the coring process and were subsampled in the field at 0.25–1.0 cm intervals using a portable core extruder system. Subsamples were kept in plastic Whirlpak® bags in the dark at +4 °C until processed. A short time (approximately 4 weeks) after arrival in the laboratory, the sediments were freeze-dried and kept in a cool, dry place until sent to the dating facilities. The long-term storage of wet samples destined for radiocarbon dating should be avoided to prevent possible contamination by fungus or other micro-organisms (Wohlfarth et al., 1998).

Loss-on-ignition (LOI), which is routinely used as a measure of organic matter content in sediments, was performed at the Laboratoire de paléoécologie aquatique, Université Laval, following standard methods outlined in Heiri et al. (2001). Biogenic silica (BSi) content, most often used as an indicator of the amount of siliceous microfossil material in sediments (Conley, 1998), was measured at the Amino Acid Geochronology Laboratory, Northern Arizona University. BSi was extracted from lyophilized sediments with Na_2CO_3 and the concentration was determined with a spectrophotometer following the procedure outlined in Mortlock and Froelich (1989).

3.2. ^{14}C AMS sample preparation

Generally slow accumulation rates in northernmost Ungava lakes (in the order of 3–5 cm ka^{-1}) require that dating of sediments be performed on small core increments (ideally 0.25–0.5 cm thickness) and use of accelerator mass spectrometry (AMS) techniques. The HA in our cores were separated from the sediment by the HA's differing solubility in acid and base extractions at Université Laval's Radiocarbon Laboratory, using the method described by Abbott and Stafford Jr. (1996). Briefly, 1–2 g of dry sediment were used for isolations, decalcified in 1.2 molar HCl at room temperature for 1 h and extracted with 1 wt% KOH at room temperature for 2–6 h. Solutions were centrifuged to remove clays and the supernatant was filtered through 0.45 μm mesh. Precipitation of humic acids was achieved with 6 molar HCl. Precipitates were freeze dried and then combusted. Combustion was done by using 5 mg of sample, 250 mg of CuO, and 50 mg of Ag in sealed, evacuated quartz tubes and finally combusted at 850 °C for 3 h. The resulting combusted CO_2 gas was sent to the Keck Carbon Cycle Facility, University of California at Irvine (USA), where AMS dating was performed. Dates in this text are given in calibrated years before present (cal yr BP), with the year 2000 AD (see below) being considered as the present, except where otherwise noted.

Radiocarbon dates were corrected for isotopic fractionation based on $\delta^{13}C$ determinations. These conventional dates were then corrected for the effect of "redeposition" by subtracting between 300 and 1000 years, except for dates falling within 1000 years of deglaciation (depending on core depth; see Results and discussion section below for details), and thereafter calibrated using the IntCal04 calibration data set in the software Calib version 5.0.1. (Stuiver et al., 2005). Following the method described in the original paper by Miller et al. (1999), the corrected errors were not included in the calibration, but were merely added to the calibrated dates. This does not have a significant effect on the resulting

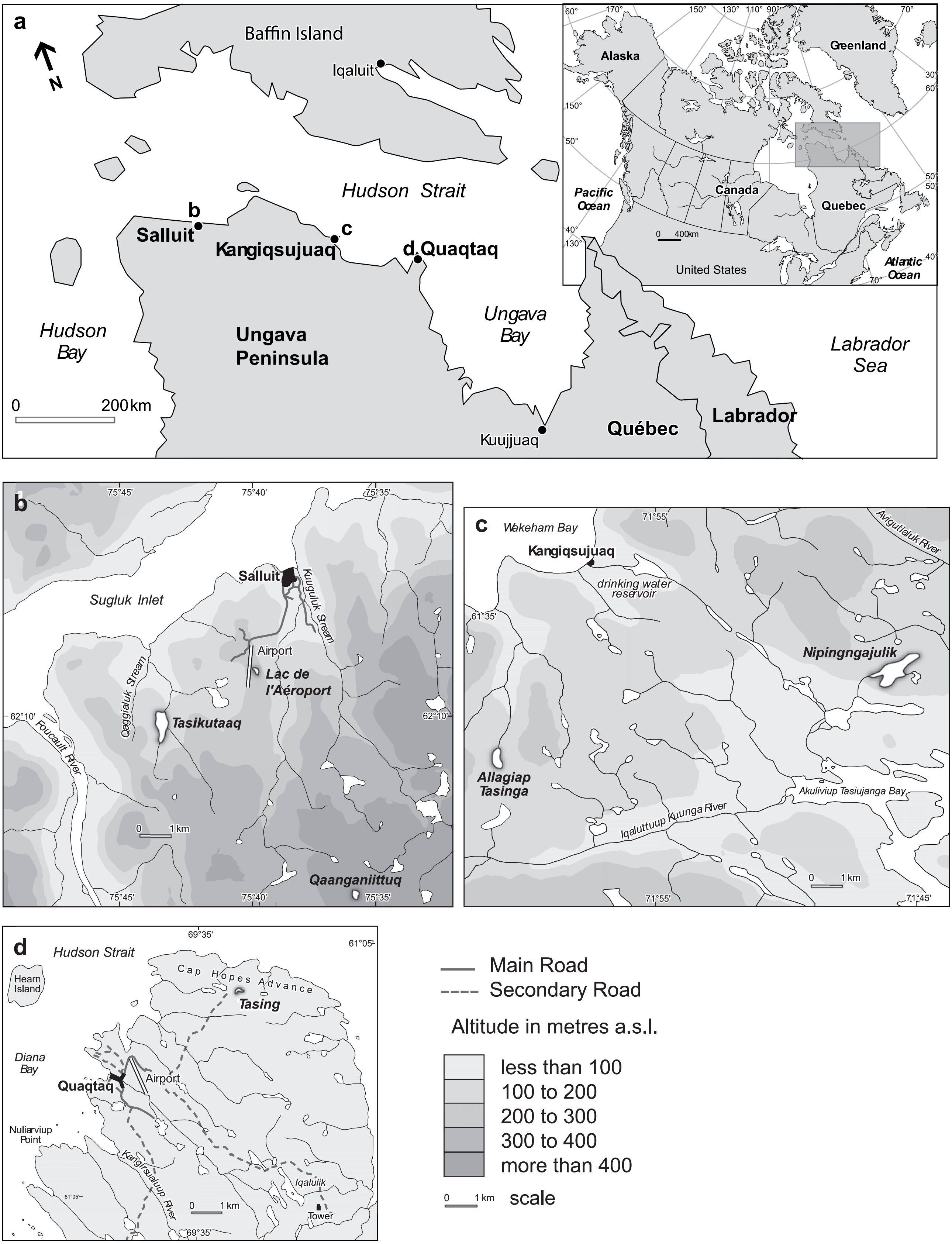

Fig. 1. Map showing the location of the study region and the study lakes in the vicinity of three Inuit communities in Nunavik, northern Ungava, Québec.

Table 1
Location, setting and sizes of the studied lakes.

Lake name (abbreviation)	Geographical coordinates	Altitude (m a.s.l.)	Distance from postglacial marine limit (m)	Area (km^2)	Max. water depth measured (m)
Lac de l'Aéroport (AER)	62°10′40.69″N, 75°39′47.69″W	220	45 above	0.0387	8.6
Qaanganiittuq (QUA)	62°07′22.68″N, 75°35′35.91″W	470	295 above	0.0622	13.9
Tasikutaaq (TKQ)	62°09′46.87″N, 75°43′14.21″W	130	55 below	0.3066	13.6
Allagiap Tasinga (AP)	61°32′28.26″N, 72°00′47.44″W	97	18 below	0.2055	9.0
Nipingngajulik (NIP)	61°34′17.28″N, 71°46′12.74″W	125	10 above	0.7925	14.5
Tasing (TAS)	61°04′12.28″N, 69°33′37.72″W	70	50 below	0.0309	3.5

median calibrated dates, but does substantially limit the amplitude of the possible age range. Finally, 50 years were added to the calibrated dates (mid-point of the 2σ range), thus displacing radiocarbon year 0 (i.e. the present) from 1950 AD to 2000 AD. This procedure facilitated comparisons with the ^{210}Pb results, which are calculated from the year of sampling (2001, 2002 or 2003, in the present case).

3.3. *Dating the recent past*

20th century atmospheric testing of nuclear weapons, especially between 1945 and the mid-1970s, injected a large amount of artificial radio-isotopes into the stratosphere, thereby increasing the concentration of ^{14}C, ^{137}Cs and ^{241}Am in the troposphere (Hua and Barbetti, 2004). Their concentration has been decreasing since the Limited Test Ban Treaty came into effect in 1963 and as such, these radio-isotopes can now be used as reliable and precise chronological markers in recent sediment accumulation. Radiocesium and ^{241}Am are now routinely used to validate age–depth models based on the natural radio-isotope ^{210}Pb. Radioactive lead falls out of the atmosphere and accumulates on the surface of the Earth where it is stored in soils, lake and ocean sediments and glacial ice, slowly losing its radioactivity. This type of ^{210}Pb is referred to as "excess", or "unsupported" ^{210}Pb, by contrast to terrestrial or "supported" ^{210}Pb, which is produced by *in situ* decay of ^{226}Ra. Unsupported ^{210}Pb has a half-life of 22.26 years; after ~7 half-lives (150 years) ^{210}Pb in a sample is below measurement capabilities, thereby allowing us to determine the age of a sample by measuring how much ^{210}Pb it contains. Despite being covered by ice for up to 10 months of the year, the majority of arctic lakes have sufficient exchange with the atmosphere to be at gaseous (e.g. CO_2, O_2, and methane) equilibrium with it and for adequate incorporation of ^{210}Pb into the sediments (reviewed in Wolfe et al., 2004). There could potentially be discrepancies in particulate equilibrium, however, where particulate matter would enter the water by entirely different mechanisms. Nevertheless, ^{210}Pb chronologies have successfully been established in northern lakes, such as in a suite of 8 lakes across Svalbard (Appleby, 2004) and 6 lakes in northeastern Québec (Laing et al., 2002).

The concentration of non-radioactive lead (^{207}Pb) in sediments can also be used as a chronological marker for recent times in certain regions of the world. In Europe, for example, stable lead isotope emissions show a rapid increase after WWII and start to decrease after 1973, when lead additives to gasoline started to be regulated in many European countries (Renberg et al., 2001, 2002). The usefulness of this indicator, as well as other trace metals, remains to be verified in many regions of the globe, including northernmost Québec.

3.4. *^{210}Pb sample preparation*

For our six sediment cores, ^{210}Pb concentrations were determined by measuring ^{210}Po, a radioactive granddaughter decay product which is detected by using alpha spectrometry. The ^{210}Po analyses were performed at the GEOTOP Laboratory, Université du Québec à Montréal (Canada) in 2002 and 2003. We report ^{210}Pb activity in disintegrations per minute per gram (dpm g^{-1}; Fig. 2). In preparation for alpha spectrometry analysis, freeze-dried sediment samples (weighing between 0.4 and 0.5 g) were ground in a mortar. A tracer was added to each sample (460 µl of ^{209}Po) and evaporated at around 200 °C. Samples were then attacked with aqua regia (5 ml $HNO_{3conc.}$ + 5 ml $HCl_{conc.}$) and heated at 150 °C for 4 h on a hot plate to destroy carbonates and organic matter. The remaining fraction was dried at 150 °C for about 2 h. HF was added and samples heated at $t < 150$ °C in order to digest and break the silicate bonds, then left to dry at 150 °C (to avoid the formation of a silicate gel). Peroxide was added and solutions evaporated at 150 °C to destroy any remaining organic matter, then samples were dissolved using $HCl_{conc.}$ and evaporated. The residues were evaporated with HCl 0.5 N and centrifuged for 10 min. Finally, they were heated at 85 °C on a vibrating hot plate for 4 h and a small amount of ascorbic acid was added to clarify the solutions while they were hot.

Additionally, we measured ^{210}Pb activity, as well as ^{137}Cs and ^{241}Am, through gamma spectrometry on two of our cores (QUA and NIP). Gamma spectrometry measures ^{210}Pb radioactivity directly, so sediments did not undergo any chemical treatment. They were compacted into plastic tubes, sealed with epoxy and left to sit in the tubes for at least two weeks before being inserted one by one into the gamma spectrometer for 24 h. Gamma spectrometry was performed at the Department of Biology, McGill University (Montréal, Canada). Results of this analysis are reported in Becquerels per kilogram (Bq/kg).

3.5. *Ascertaining reservoir effects*

The first step in establishing a reliable lake core ^{14}C chronology is to determine if a reservoir effect exists in the lake (i.e. when the ^{14}C activity of the lacustrine carbon pool is significantly different – usually less – than the ^{14}C content of the contemporaneous atmosphere). Dating living aquatic plant material (Abbott and Stafford Jr., 1996) determines whether or not the lake-DIC pool and aquatic biota are in equilibrium with the atmospheric $^{14}CO_2$.

Bedrock carbonate sources, combined with long water residence times, can result in a hard-water effect in lakes (Aravena et al., 1992; MacDonald et al., 1987, 1991). The hard-water effect is caused when geologically ancient (^{14}C-depleted) limestones, dolomites and, less commonly, pedogenic carbonate dissolve and contribute carbonate and bicarbonate to lake waters. The ^{14}C-depleted geologic carbonate decreases the water's $^{14}C/^{12}C$ value, and causes aquatic plants synthesizing aquatic CO_2 to have lower than normal $^{14}C/^{12}C$ values. The amount of depletion and subsequent age-error due to carbonate reservoir effects is determined by mixing ratios of geologic and atmospheric CO_2.

If isotopic equilibrium exists between the lake water and atmospheric CO_2, it can be assumed that submerged aquatic plants constitute an excellent material for obtaining reliable dates from

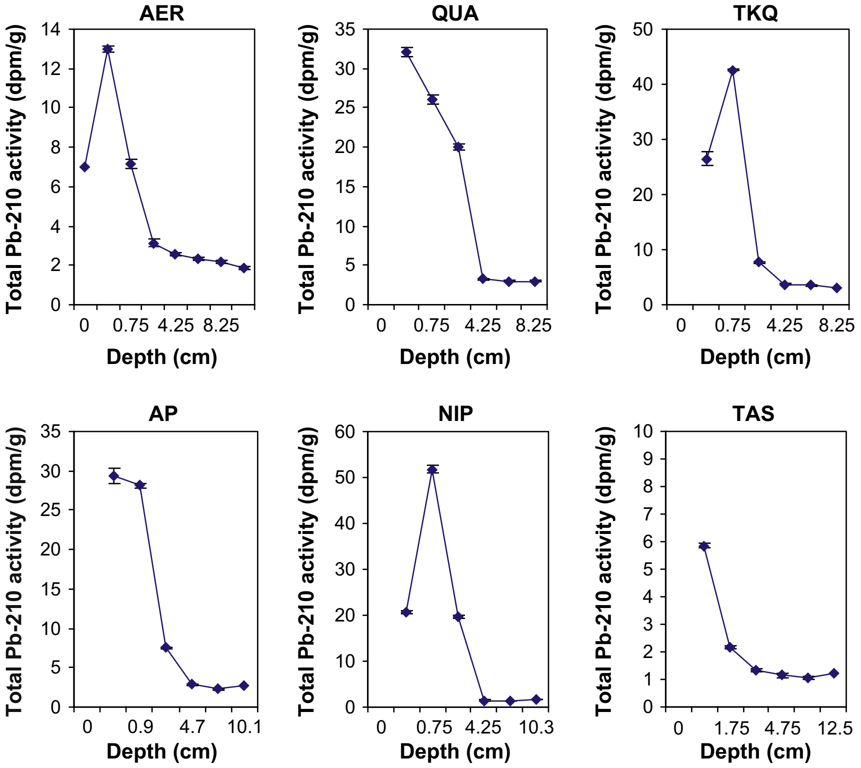

Fig. 2. Total (supported + unsupported) ^{210}Pb activity obtained by alpha spectroscopy in the six sediment cores from northernmost Ungava lakes, plotted against sediment depth (cm).

a core. Because emergent plants are so rare in arctic settings and reworking of ancient emergents is possible, submerged aquatics become the single best dating option. This is most often the case with well-mixed lakes or lakes with short residence times, and which are within crystalline bedrock settings and are not significantly impacted by carbonate sources. In this setting, if an apparent reservoir effect (dates that are seemingly too old) is detected by dating of other types of material (i.e. other than aquatic plants) from further downcore such as bulk sediment and humic acids, it will most likely be due to inputs of "old carbon" from terrestrial sources in the watershed, a process termed "redeposition" by MacDonald et al. (1991). On the other hand, if the lake-DIC pool is ^{14}C-depleted compared to atmospheric $^{14}CO_2$ (i.e. the $^{14}C/^{12}C$ ratio of the analysed living plant material has a fraction modern (Fm) less than 1.00), terrestrial macrofossils will constitute the best option for obtaining a more accurate chronology for the core. In the case where terrestrial macrofossils or other externally-derived time markers (such as varves or tephra layers) are absent from the sediment record of a hard-water lake, other dating techniques must be considered, such as optically stimulated luminescence (OSL) of fine grain quartz (4–20 μm) (e.g. Shen et al., 2007). However, the full potential and drawbacks of this technique have not yet been fully explored in relation to lacustrine environments, and accurate interpretation of OSL results requires substantial knowledge of sedimentary processes, efficiency of solar resetting and environmental radioactivity (Wolfe et al., 2004).

Living aquatic plant material was not analysed in our study lakes, due to logistic constraints. Nevertheless, our study sites lie on granitic bedrock, far from potential carbonate sources and we therefore expect the lacustrine carbon pool in these lakes to be at equilibrium with regional atmospheric $^{14}CO_2$. Although the study region is located in the zone of continuous permafrost, we lack information on the local configuration of the beneath-lake permafrost. Therefore, we cannot at this stage make any assumptions on the presence or absence of possible groundwater effects on the lake waters. However, it is not likely that distant carbonate deposits could be connected to the lakes via long-distance aquifers, since carbonates are uncommon in northern Ungava, which is mostly made-up of metasedimentary and metavolcanic rocks (Daigneault and Bouchard, 2004).

3.6. Anchoring the chronology

If aquatic plant macrofossils are present and can be dated, it is recommended that HA from the same levels also be dated in order to establish the presence and magnitude of a depositional lag effect at that particular core depth. At least one such level, where the dating of different materials can confirm the age of the deposit, should ideally serve to anchor a HA chronology. Since physical and geochemical processes may not be uniform over thousands of years, an ideal procedure would be to have anchors around the top, middle and bottom of the core (although one core position is better than none, it is important to keep in mind that humic acid–macrofossil relationships probably do not remain unchanged over thousands of years). In this way, it becomes possible to date other levels where macrofossils are absent, using solely HA with more precision. However, in reality, aquatic macrofossils are generally rare (either because they are absent or present in too little mass) in sediments of these types of ecosystems and HA often represent the only option for obtaining a chronology (terrestrial macrofossils are also very rare), as was the case with our sediment cores from northern Ungava lakes. In such a case, it would be useful to determine the carbon to nitrogen ratio (C/N) of the organic matter in the sediment, as well as its $\delta^{13}C$ signature. These proxies can serve to estimate the original proportions of land-derived and aquatic plant material, as well as the history of productivity and carbon recycling in the lake (Meyers and Teranes, 2001). Samples containing a higher proportion of material of aquatic origin should then be favoured as they are likely to contain less "old carbon" from the catchment area.

Although it has been suggested that aquatic animal macrofossils such as chironomid head capsules are suitable to develop age–depth chronologies of lake sediment cores (e.g. Fallu et al., 2004; Jones et al., 1993), they can also potentially present further complications for dating (e.g. Weckström et al., 2006). AMS dating of sedimentary chironomid head capsules needs to be tested further in order to clarify its underlying mechanisms; therefore, despite the fact that chironomids were present throughout our study cores, no attempt was made to perform ^{14}C analysis on this material.

3.7. Corrections for old carbon sequestration and calibration

By dating aquatic moss macrofossils and HA from the same levels in a core from Baffin Island, Miller et al. (1999) demonstrated that, in the early stages of ecosystem development when there is probable absence of an accumulated soil carbon pool, dates obtained by HA are less likely to be offset by admixture of older material from the catchment area. But as soils develop, the discrepancy between the ages of the two materials increases, averaging about 300 years for the postglacial period (covering c. 10 500 years in southeastern Baffin Island). Thus, Miller et al. (1999) suggest that a correction of 300 ± 300 years be systematically applied to HA dates, except within 1000 years of deglaciation, when no correction is theoretically needed. The 300 years must be subtracted from the date before calibrating it, which is why the inherent error of ±300 years is retained. This technique has been successfully applied to other cores from Baffin Island (Wolfe, 2003; Wolfe and Perren, 2001). In two of our cores, the ^{210}Pb and ^{14}C activities obtained from the same levels suggest that this difference can be even greater in the recent sedimentary records of some high-latitude lakes (see Results and discussion). Since we knew the offset was greater than 300 years at the top of the cores, we adjusted the conventional dates obtained from the same levels as the ^{210}Pb curve to fit these data in cores NIP and QUA. This obviously increases the possible error associated with each date, but presents a more realistic estimation of the offset between the time of deposition in the catchment and the time of deposition in the lake basin itself. Therefore, this adjustment not only gives us information on recent catchment processes, but also provides a better understanding of how they have changed throughout the postglacial period.

The last step in the process of converting a radiocarbon date into a calendar date is to generate a point estimate of the calibrated date range. However, no single value can replace the complete probability distribution, which should be used whenever possible. The weighted average of the probability distribution function and the median of the 2σ ranges have been suggested as the best central-point estimates (Telford et al., 2004a,b). When it was needed for comparison with ^{210}Pb age estimates, we used the latter in the context of the calibrated age range.

4. Results and discussion

4.1. ^{210}Pb

In our study lakes, the ^{210}Pb activity (acquired with alpha spectrometry) vs depth profiles display exponentially decreasing activity, except for inversions in the top 1 cm of three lakes: AER, NIP and TKQ (Fig. 2). These inversions could be the result of an accelerated sedimentation rate, or more likely of bioturbation in the flocculent surface sediments. For example, chironomid larvae, which were present and active at the surface of some of the cores during retrieval, have been observed to burrow down to 3 cm depth in some arctic lakes (Kirchner, 1973). Total ^{210}Pb activity in the core tops varied substantially between lakes, ranging from 5.9 dpm g^{-1} (in TAS) to 51.8 dpm g^{-1} (in NIP), but remained within the reported latitudinal range of ^{210}Pb activity in surface air for latitudes 60–62° N (see Wolfe et al., 2004). The level at which total (i.e. supported + unsupported) ^{210}Pb activity becomes constant was used to estimate the 150 year "limit" of detection for unsupported (or "excess") ^{210}Pb (see Wolfe et al., 2004 for overview). In our cores, this limit was reached between 2.75 and 6.25 cm depths, providing us with a marker with which to evaluate the results from our AMS ^{14}C ages. The constant rate of supply model (Oldfield and Appleby, 1984) was applied to the gamma spectrometry ^{210}Pb data obtained for cores NIP and QUA because, in this case, the ^{137}Cs and ^{241}Am data necessary to validate it were available (Figs. 3 and 4, respectively). The results from alpha and gamma spectrometry are consistent in the cases where both were applied to the same cores, in agreement with previously published results supporting the general comparability and reliability of the two methods (Tanner et al., 2000; Zaborska et al., 2007).

4.2. AMS ^{14}C

In cores NIP and QUA, for which we had ^{210}Pb data from both alpha and gamma spectrometry, we performed AMS dates on HA from 4 to 4.5 cm depth, which is the level of the detection limit for unsupported ^{210}Pb and should correspond to an age of approximately 150 years. The AMS dates of 1026 and 1142 cal yr BP showed offsets of 876 and 992 years with respect to the ^{210}Pb detection limit, respectively (1026–150; 1142–150). Based on these results, we estimated the ages obtained from HA near the core tops to be ~1000 cal yr too old in our study lakes. Our data compare well with the results obtained by Abbott and Stafford Jr. (1996) for HA from surficial sediments in Baffin Island lake watersheds, which showed apparent ages of ~1000 ^{14}C years, despite the ^{14}C activity of living aquatic vegetation being 115% Modern. In light of these results, it seems necessary to subtract more than 300 years from the radiocarbon dates performed near the core tops in order to obtain a more realistic chronology.

Of the sediment records recovered from lakes in the vicinity of Salluit (62°10′N, 75°40′W), the core from Lac de l'Aéroport (AER; Fig. 5a) covered the longest period of the postglacial. This core presents a lithology consisting of weakly organic clayey silt from 50 to 46 cm, followed by a 1-cm transition to brownish-gray silty gyttja up to about 26 cm. The rest of the core consists of olive–brown silty gyttja. The date obtained at the base of the core (49.5–50 cm depth) showed an inversion with the two dates obtained from up-core levels at 36–36.5 and 26–26.5 cm, being about 500–600 cal yr younger. We attempted to obtain dates from in-between levels (47–47.5 and 48.5–49 cm) to confirm the basal age, but these samples did not yield enough HA to produce a reliable date (G. Labrecque, U. Laval Radiocarbon Laboratory, personal communication). These results, along with lithology, LOI and biogenic silica data (averaging 2% and 2 mg g^{-1}, respectively, between 40 and 50 cm depth), suggest that the base of core AER represents a period of extremely low lake productivity, and/or of high input of inorganic sediment from the catchment. The fact that the dates obtained from the two upper samples were 10 cm apart and yielded similar dates (8120 ± 92 and 7980 ± 64 cal yr BP) is an indication for extremely rapid sediment accumulation, probably due to high inorganic inputs from the catchment associated with delayed development of terrestrial vegetation and soils. The dates obtained for this early period of the core are in good accordance with existing dates performed on marine shells (7970 ± 250 radiocarbon years in

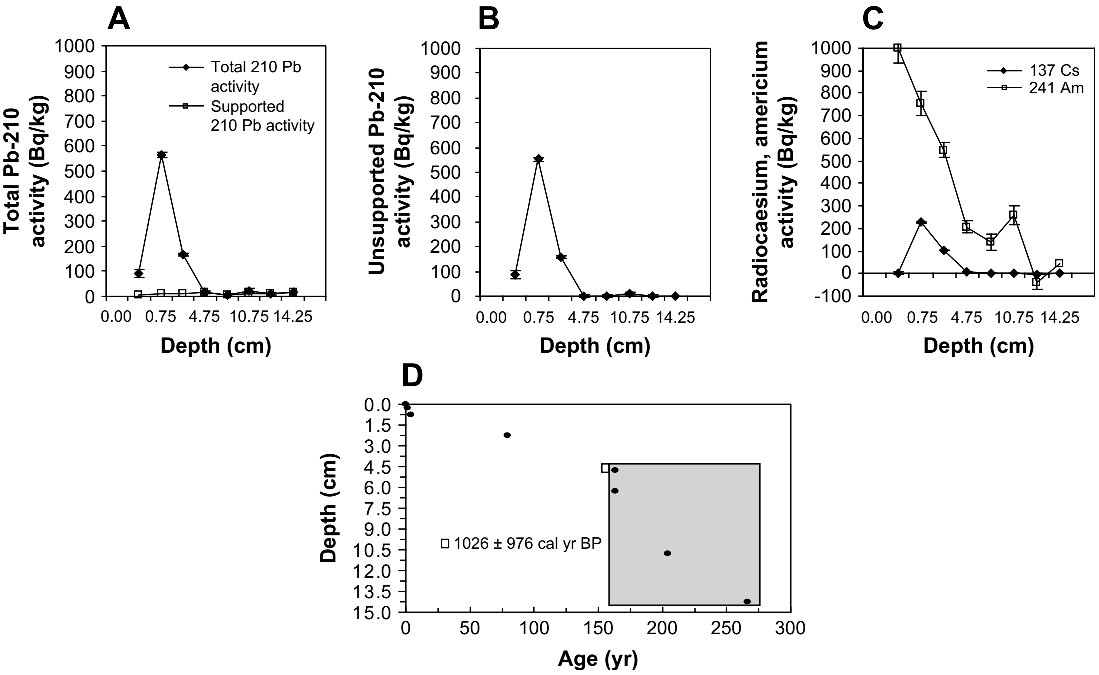

Fig. 3. Results of gamma spectrometry performed on sediments from the NIP core; total and supported ^{210}Pb activity (A), unsupported ^{210}Pb activity (B), ^{137}Cs and ^{241}Am activity (C), age–depth inferred by CRS model (D). Ages in D are from 2003, the year of sampling. Data points in the gray box are unreliable because they are beyond the 150-year resolution of ^{210}Pb. White box indicates the calibrated ^{14}C age for that depth.

Gray et al., 1993; which corresponds to a calibrated age between 9135 and 7978 cal yr BP, after reservoir correction and addition of 50 years) found near the maximum marine limit, located only a few hundred meters away from the lake, at a slightly lower altitude (based on the observations of Kasper, 1995). This supports the idea that dates performed on HA at a level of early lake ontogeny in recently deglaciated landscapes are highly reliable. The high initial sedimentation rate might also possibly reflect a catastrophic event, such as a subaquatic landslide, but there is no clear evidence to support this. The presence of "old carbon" in the meltwater of the retreating icefront could also account for the older age of the sediments during this short timeframe. Finally, due to the rapid accumulation rate at that time, we opted to assign a global age of 8200–7500 cal yr BP to the interval comprised between 50 and 25 cm.

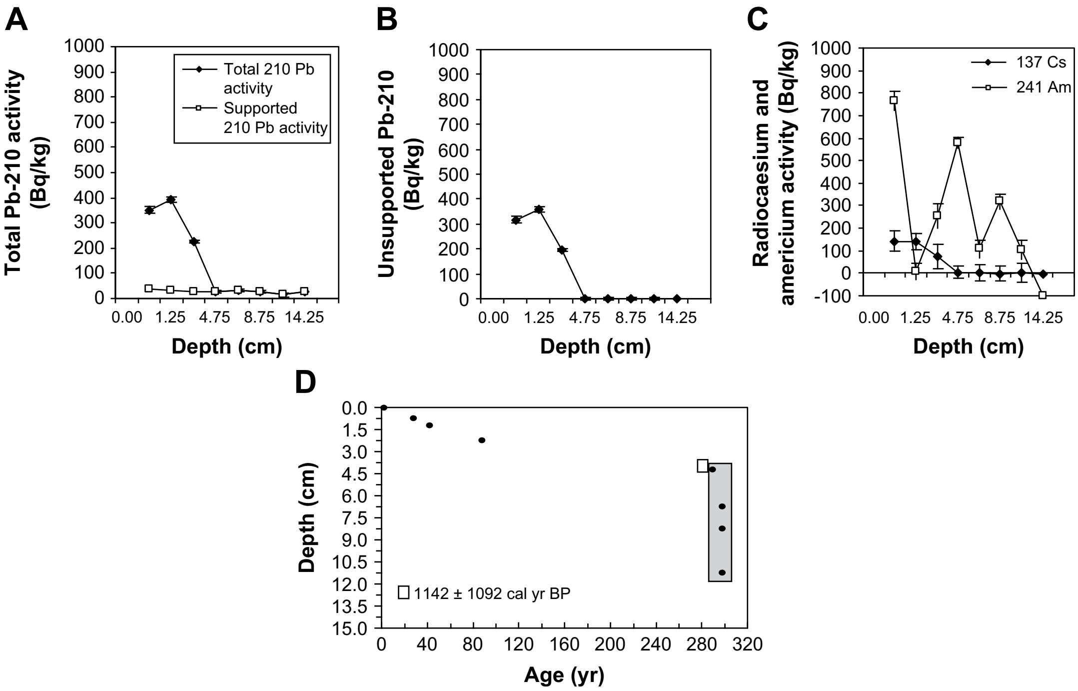

Fig. 4. Results of gamma spectrometry performed on sediments from the QUA core; total and supported ^{210}Pb activity (A), unsupported ^{210}Pb activity (B), ^{137}Cs and ^{241}Am activity (C), age–depth inferred by CRS model (D). Ages in D are from 2002, the year of sampling. Data points in the gray box are unreliable because they are beyond the 150-year resolution of ^{210}Pb. White box indicates the calibrated ^{14}C age for that depth.

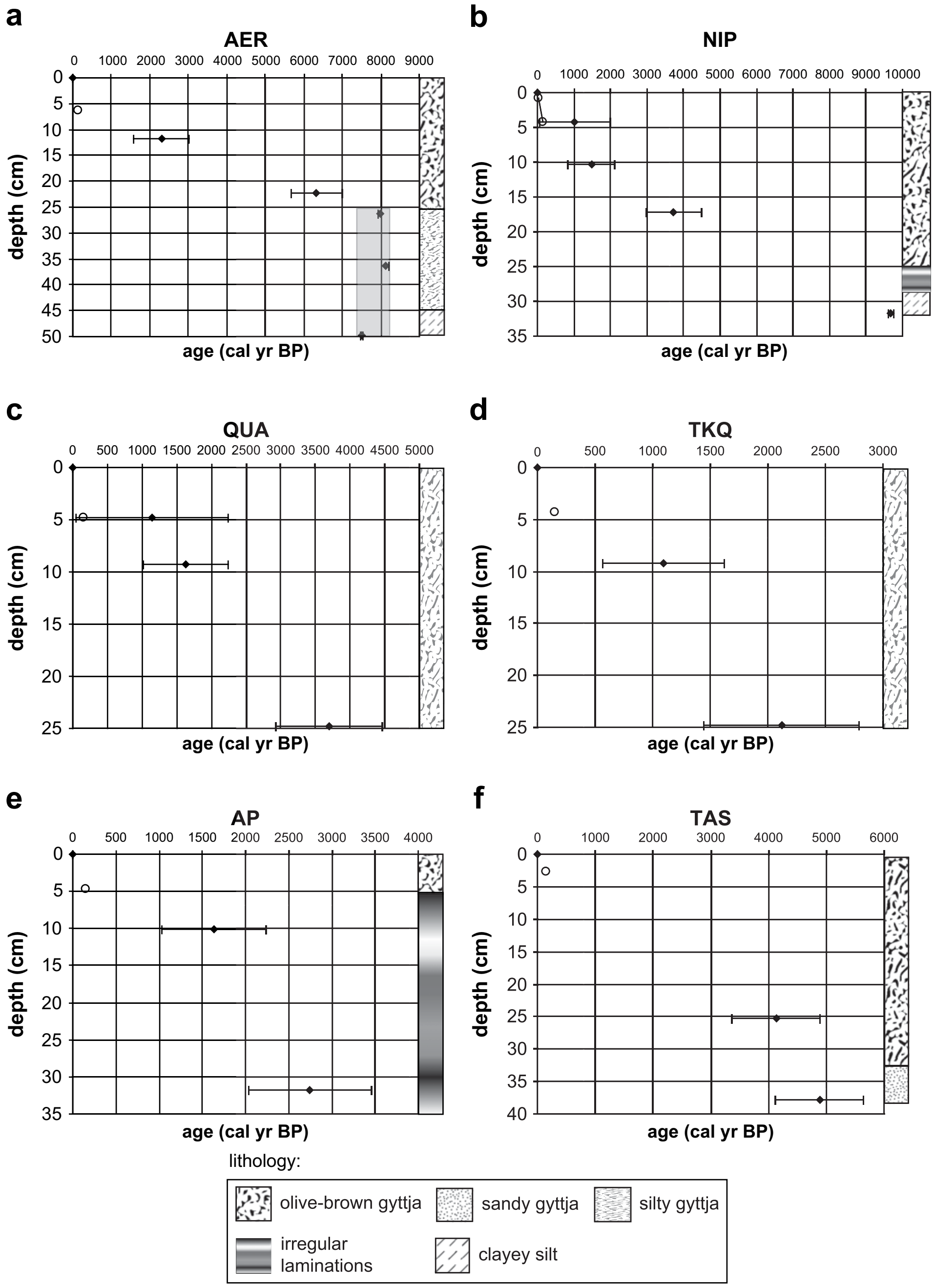

Fig. 5. Lithologies and age vs depth in six sediment cores from northernmost Ungava lakes. Full diamonds indicate AMS dates from HA and open circles indicate the depth at which total (i.e. supported + unsupported) ^{210}Pb activity becomes constant and corresponds to about 1850 AD (or 150 BP).

Qaanganittuuq (QUA; Fig. 5c) and Tasikutaaq (TKQ; Fig. 5d), the other cores recovered from lakes near Salluit, both measured 25 cm in depth and consisted of uniform brown silty gyttja. The bottom of core QUA yielded a date of ~3700 (±770) cal yr BP, whereas that of core TKQ yielded a much younger age (~2100 ± 700 cal yr BP). Based on the ageing effect associated with the date obtained at 4.25 cm in the QUA core (Table 2), it is likely that the minimal ages of these two cores would be located within the younger portion of their associated error brackets.

Two 32 cm-long cores were recovered from our study lakes near Kangiqsujuaq (61°35′N, 71°55′W). The core from large Nipingngajulik (NIP; Fig. 5b) displays the oldest sequence recovered in this study (basal date of 9680 ± 80 cal yr BP) and probably covers the entire postglacial period in the region. This presumption is supported by: a) the lithostratigraphic changes that include silty clay in the lowermost strata (32–28 cm), presumably of glaciolacustrine origin because the lake lies about 10 m above the presumed maximum postglacial marine limit, b) the shifts in the diatom and chironomid fossil assemblages (Saulnier-Talbot, 2007), and c) the few published data on the timing of the retreat of the Laurentide Ice Sheet in the region, which is believed to have receded between 10 ka and 7 ka ^{14}C (Gray et al., 1993). Dark laminations occurred in the sediment core between 28 and 25 cm depth, followed by brown silty gyttja up to about 10 cm. The rest of the core consisted of homogenous olive–brown gyttja.

The second lake cored in this region, the smaller Allagiap Tasinga (AP; Fig. 4e), had a complex lithology of alternating brown and olive gyttja, interstratified with reddish, grayish and black

Table 2

Results of AMS ^{14}C analyses performed on sedimentary humic acids from northernmost Ungava lakes.

AMS lab no.	Core depth (cm)	Uncorrected ^{14}C age (^{14}C yr BP)	δ^{13}C (‰) (VPDB)	Conventional age (δ^{13}C corr.) (^{14}C yr BP)[c]	Correction for "lag time" (^{14}C yr BP)	Calibrated age range at 1 SD (cal yr BP)	Probability distribution 2σ ranges	Median value (cal yr BP)	Adjustment to 2000 AD (cal yr BP$_{+50}$)
UCI-28791[a]	AER(s)[b] 11.5–12	2510 ± 15	−22.6 ± 0.6	2550 ± 18	2250 ± 300	1542–2957	1.0	2250	2300 ± 708
UCI-21737	AER 22–22.5	5750 ± 20	−22.0 ± 0.2	5800 ± 20	5500 ± 300	5607–6955	1.0	6281	6331 ± 674
UCI-24214	AER 26–26.5	7025 ± 20	−20.0 ± 0.9	7110 ± 25	7110 ± 25	7872–7974	1.0	7923	7973 ± 51
UCI-21584	AER 36–36.5	7205 ± 25	−23.3 ± 0.8	7230 ± 28	7230 ± 30	7974–8157	1.0	8066	8116 ± 92
UCI-17776	AER 49.5–50	6485 ± 20	−23.3 ± 0.6	6520 ± 22	6520 ± 20	7420–7474	1.0	7447	7497 ± 27
UCI-21581	AP(k) 10–10.25	1980 ± 25	−26.3 ± 0.5	1960 ± 26	1660 ± 300	976–2185	0.9	1581	1631 ± 605
UCI-17773	AP 31.5–32	2910 ± 20	−25.2 ± 0.6	2910 ± 22	2610 ± 300	1987–3406	0.9	2697	2747 ± 710
UCI-24215	NIP(k) 4–4.5	1075 ± 15	−24.4 ± 0.5	1090 ± 17	190 ± 900	0–1952	0.9	976	1026 ± 976
UCI-21580	NIP 10–10.5	1805 ± 25	−25.5 ± 0.4	1800 ± 26	1500 ± 300	793–2061	0.9	1427	1477 ± 634
UCI-21579	NIP 17–17.5	3700 ± 25	−24.5 ± 0.2	3710 ± 25	3410 ± 300	2924–4441	0.9	3683	3733 ± 759
UCI-17767	NIP 31.5–32	8610 ± 25	-19.7 ± 0.3	8700 ± 25	8700 ± 25	9552–9703	0.9	9628	9678 ± 76
UCI-28790	QUA(s) 4–4.5	1285 ± 15	−28.9 ± 0.4	1220 ± 16	220 ± 1000	0–2183	0.9	1092	1142 ± 1092
UCI-21583	QUA 9–9.5	2060 ± 25	-31.0 ± 0.8	1960 ± 28	1660 ± 300	976–2185	0.9	1581	1631 ± 605
UCI-17774	QUA 24.5–25	3710 ± 20	−28.3 ± 0.4	3660 ± 21	3360 ± 300	2877–4414	1.0	3646	3696 ± 769
UCI-21582	TAS(q) 25–25.5	3865 ± 30	−19.7 ± 0.4	3950 ± 31	3650 ± 300	3323–4836	0.9	4080	4130 ± 757
UCI-17775	TAS 37.5–38	4440 ± 20	−17.8 ± 1.0	4560 ± 26	4260 ± 300	4075–5588	0.9	4832	4882 ± 757
UCI-21578	TKQ(s) 9–9.5	1360 ± 30	−23.1 ± 0.2	1390 ± 30	1090 ± 300	516–1574	0.9	1045	1095 ± 529
UCI-17770	TKQ 24.5–25	2285 ± 15	−23.6 ± 0.3	2360 ± 16	2060 ± 300	1395–2746	1.0	2071	2121 ± 676

[a] UCI = University of California Irvine.

[b] Northern village nearest to the lake identified with a letter in parentheses (s = Salluit, k = Kangiqsujuaq, q = Quaqtaq).

[c] Conventional age is the δ^{13}C-corrected AMS ^{14}C measurement that is used for all subsequent calibrated ages.

laminae. It remains to be determined if these lithostratigraphic changes, perhaps caused by fluctuating water levels, had an effect on the various biotic assemblages, the food web, and carbon cycles in this lake. The ^{14}C age obtained for the base of this core suggests that it covers <2500 cal yr.

The 38 cm-long core recovered from Tasing (TAS; Fig. 4f), on Cape Hope's Advance near Quaqtaq (61°05′N, 69°63′W) spans a maximal time period <5000 cal yr BP. The core consisted of brown gelatinous sandy gyttja from 38 to 33 cm depth, and of olive–brown sandy gyttja above 33 cm.

To the best of our knowledge, three other studies have dated lake sediment cores in the northern Ungava region. One of these studies (Bouchard, 1989) attempted to assign an age to a core recovered from the Nouveau-Quebec Crater lake (official name: Pingualuk; 61°16′37″N, 73°39′38″W) by radiocarbon dating of bulk sediments. Although the crater lake has little relevance with the type of systems investigated in our study, a core collected from a small shallow lake located just outside the crater's rim provided results comparable with our study lakes. AMS of a bulk sediment sample from Lac du Sud-Ouest (Richard et al., 1991) dates the transition between slightly organic clayey silt and silty gyttja (depth of 50 cm) to 6920 ± 90 ^{14}C years BP, corresponding to a calibrated date of 7772 ± 163 cal yr BP. The postglacial palynological study of the western Ungava Bay sector by Richard (1981) established the timing of the transition between inorganic sediments and gyttja accumulation by ^{14}C dating of basal bulk organic sediments (i.e. ∼5–20 cm thickness) at between 6820 ± 155 and 6460 ± 160 ^{14}C yr BP in the Quaqtaq region, which corresponds to 7689 ± 257 cal yr BP and 7311 ± 312 cal yr BP, respectively.

5. Conclusion

The comparison of ^{14}C and ^{210}Pb activities from the same stratigraphic levels in two sediment cores indicated that, similar to findings from Baffin Island, redeposition of terrestrial organic matter contributes to an apparent ageing of recent lake sediments in northernmost Ungava lakes. This suggests that HA might be affected by terrestrial carbon input more than was initially thought. However, based on our observations, we suggest that instead of systematically applying a constant ageing factor such as the one proposed for Baffin Island (i.e. 300 ± 300 years average), an effort should be made to evaluate the offset (or apparent ageing) of the HA radiocarbon dates throughout the core (when possible), even though this results in much larger errors, especially when the dates are calibrated. In soft water lakes, this evaluation should ideally be conducted by dating of aquatic plant material and HA from the same levels. Additionally, since we know that the ages obtained using HA in this type of environment are too old, logic dictates that it is wiser to consider the younger portion of the error bracket when attempting to evaluate the true age of the core depth associated with each date.

Our results confirm that radiocarbon dates on humic acids can provide accurate age estimates for sediments deposited within 1000 years of deglaciation. This interpretation is based on the high similarity between ages performed on humic acids and marine shells. Based on the current state of our knowledge, radiocarbon dating of HA should be considered the preferred method for assigning dates to initial postglacial lacustrine accumulation. However, the method presents complications for dating sediments that significantly postdate time-of-deglaciation and especially at core intervals where paired humic acid and aquatic plant fossil dating is not possible. As such, this question needs to be addressed further if more reliable lacustrine chronologies are to be developed for extremely unproductive environments.

Establishing reliable age–depth chronologies is essential for the proper analysis and interpretation of the paleoenvironmental records contained in high-latitude lacustrine sediments. AMS ^{14}C and other dating methods such as ^{210}Pb must be properly understood and applied to improve the accuracy of lake sediment chronologies. There is no better solution to gaining higher accuracy than to produce an ever larger set of dates for each lake core. Unfortunately, the high cost of AMS radiocarbon analyses still limits the number of data points depending on the available scientific budgets. In order to increase the reliability of chronologies, a better understanding of individual lake biogeochemistry must be achieved in paleolimnological studies. To this end, it is necessary to emphasize proper sampling and dating of appropriate materials, including living and fossil aquatic mosses when they are available, as well as organic deposits from the lake catchments. If a core chronology can be well anchored by dating more than one material from the same level, then dating humic acids becomes a valuable alternative because they enable paleolimnologists to date practically any stratigraphic level. This is especially helpful in cases where no aquatic plant macrofossils can be found at depths where significant paleoenvironmental changes are identified by shifts in sedimentary biological and geochemical proxies.

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