A record of climate over the last millennium based on varved lake sediments from the Canadian High Arctic

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Abstract: A varved sediment record that extends back over the last millennium was recovered from Lower Murray Lake, northern Ellesmere Island, Nunavut, Canada (81°20′N, 69°30′W). Flatbed scan images and backscattered electron images were analysed to provide varve thickness and other quantitative sedimentary indices on an annual basis. In many studies of lakes from the High Arctic, varve thickness is a good proxy for summer temperature and we interpret the Lower Murray Lake varves in this way. On that basis, the Lower Murray Lake varve thickness record suggests that summer temperatures in recent decades were among the warmest of the last millennium, comparable with conditions that last occurred in the early twelfth and late thirteenth centuries, but estimates based on the sediment accumulation rate do not show such a recent increase. The coldest conditions of the 'Little Ice Age' were experienced from ~AD 1700 to the mid-nineteenth century, when extensive ice cover on the lake led to widespread anoxic conditions in the deepest parts of the lake basin. An overall decline in median grain size over the last 1000 years indicates a reduction in the energy available to transport sediment to the lake. Many of these features of the record are also observed in other palaeoclimatic records from the North American Arctic. The very recent appearance of the diatom *Campylodiscus*, which was not observed throughout the record of the last millennium, suggests that a new threshold in the ontogenetic development of the lake has now been passed.

Key words: Palaeoclimate, varves, lake sediments, last millennium, 'Little Ice Age', High Arctic, Canada.

Introduction

North of the Arctic treeline, there are few options for obtaining palaeoclimatic information (Bradley, 1990). This is particularly unfortunate in that instrumental records are very short (generally < 60 years in the North American sector). Thus, the need for high resolution (annually resolved) palaeoclimatic data to place recent observations in perspective extends right up into the mid-twentieth century. This need is all the more pressing because virtually all GCM simulations of future climate identify the Arctic as the region where changes are expected to be most extensive, so we need to place these projected changes in the context of past Arctic climate variability. We know, from large-scale studies of climate variability over the last century and the last millennium, and from model simulations, that temperature changes tend to be amplified at high latitudes – and this seems to be true both for the periods of 'natural' and of anthropogenic forcing (Moritz *et al*., 2002; Holland and Bitz, 2003; Arctic Climate Impacts Assessment (ACIA), 2005; see also the discussion at http://www.realclimate.org/index.php?p=234, last accessed 19 October 2007). Palaeoclimatic records from high latitudes may thus capture changes that have affected the hemisphere as a whole, whereas the record is more muted at lower latitudes. This polar amplification is related to feedbacks associated with

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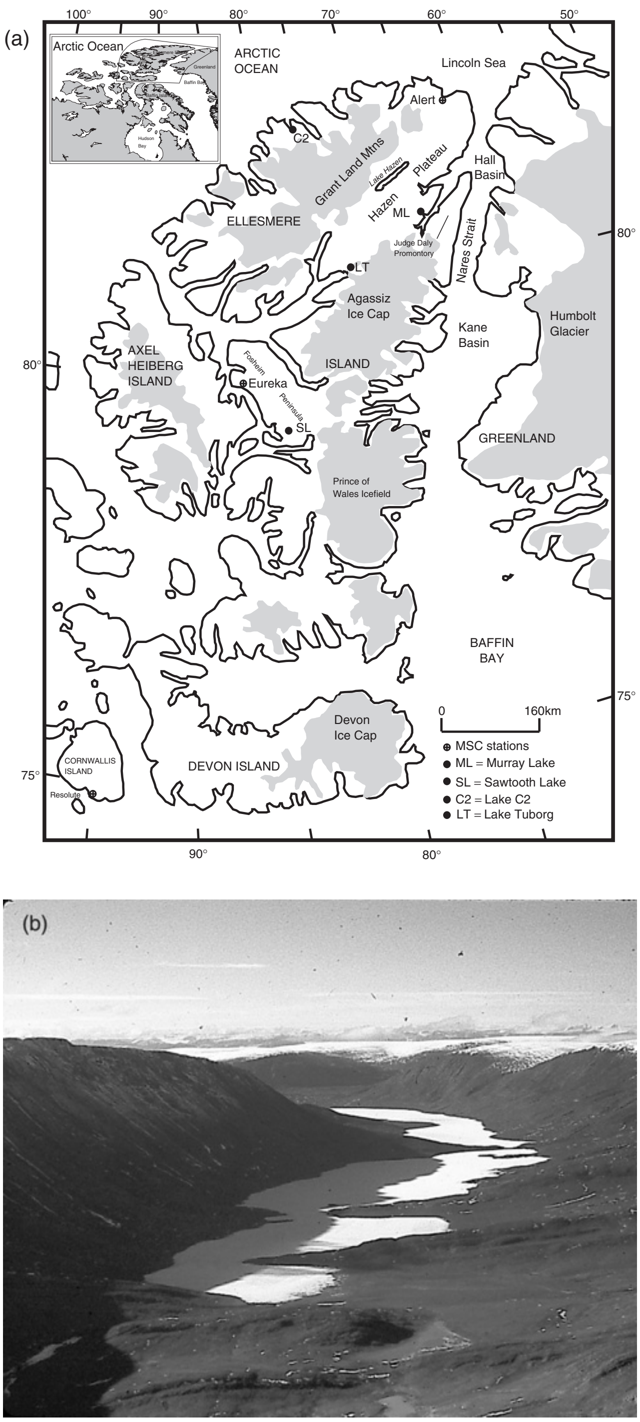

Figure 1 (a) Map of Ellesmere Island and surrounding arctic islands. Included are long-term meteorological stations at Resolute, Eureka and Alert. Also included are the Murray Lakes, and other lakes mentioned in the text where annually laminated records have been recovered (Sawtooth Lake, Lake Tuborg and Lake C2). Shaded areas denote areas currently glacierized. (b) View of the Murray Lakes looking to the north-northwest (LML in foreground)

snow and ice, and is most clearly seen in high latitude proxies where anomalously cold or warm conditions can have dramatic effects on systems (such as trees or lakes) that have a narrow summer response window. Palaeoclimatic proxies from the High Arctic should therefore be sensitive indicators of larger-scale changes, and help to identify the important forcing factors that have affected climate on a much larger scale. With that goal in mind, we describe here studies of varved lake sediments from northeastern Ellesmere Island, in the Canadian High Arctic.

Description of study site

Upper and Lower Murray Lakes (unofficial names, herein referred to as UML and LML) are a pair of relatively deep lakes (~82 and ~47 m, respectively) on the eastern margin of the Hazen Plateau, northern Ellesmere Island, Nunavut, Canada (81°20′N, 69°30′W; Figure 1a). The lakes, separated by a shallow spillway, occupy the bottom of a glacially eroded valley with surface elevations of 107 and 106 m above sea level, respectively. They were selected for palaeoclimatic investigation based on their deep basins (which we have found elsewhere in the High Arctic favours the accumulation of laminated sediments), relatively simple catchment areas and fairly homogeneous bedrock in their watersheds.

The Murray Lakes valley (Figure 1b) is a north–south trending U-shaped valley that was occupied by ice during the last glaciation. Shells in marine sediments at the head of Archer Fiord at 88 m a.s.l. and less than 3 km from the lakes (Figure 2) provide a minimum age of 6.9 ka radiocarbon years BP for marine emergence in this area (England, 1983). Thus the lakes are above the local marine limit. Ice probably retreated from the valley shortly before this time, though locally extensive ice caps probably remained on the adjacent uplands, and these would have drained into the Murray Lakes valley. Whether these ice caps subsequently disappeared altogether, only to re-develop in the late Holocene is unknown, but this suggestion has been made for other small plateau ice caps in the High Arctic (Koerner and Paterson 1974). If so, this would have greatly reduced runoff into the lakes during the mid Holocene.

The lake basins are currently constrained by bedrock and colluvium. However, there are glacio-fluvial deposits at the outlet of the lower lake that indicate the lakes may have been dammed by glacial outwash just after the last glacier retreated from the valley. It is likely that the lakes fluctuated in level before eroding an outlet through these deposits and maintaining their current levels. Together, the Murray Lakes have a combined watershed area of 269 km^2 (Figure 2). However, UML receives the majority of the runoff directly from a river that drains the upland area (194 km^2) to the west of the lakes. The watershed area that feeds UML includes a large ice cap and, from the size and appearance of the delta and smaller alluvial fans, receives much more sediment than LML. There is likely spill-over of runoff from UML to LML during the melt season. However, the spillway that connects the two lakes is shallow (less than 1 m), narrow (less than 15 m) and is maintained by a bedrock threshold (Figure 3). This threshold would limit all but low-density overflows from being transported to LML. LML receives the majority of its inflow from the watershed area to the east. The runoff comes from a small inlet stream at the northeast end of the lake and a larger stream at its south end that drains the two small ice caps to the east (Murray Ice Cap and Simmons Ice Cap). Currently these have no significant input, but if the ice caps were larger in the past there would have been direct runoff into LML.

Because temperatures generally remain below freezing from late August until late May, ice covers the lakes for ~11 months of the year and is 1.5–2 m thick by the end of the winter season. On LML, a moat at the edge of the ice develops in the summer, accompanied by a thinning ice cover and, on rare occasions, the ice cover may completely break up by late August/early September before quickly reforming once again as winter sets in. Because of this extreme seasonality of runoff, sediment flux to the lakes is restricted to a short melt season (June–August); coarse sediment settles to the lake floor in the brief summer period, whereas winter months are characterized by finely suspended sediment settling out below the ice cover. These changing energy conditions are thus ideal for the formation of varves.

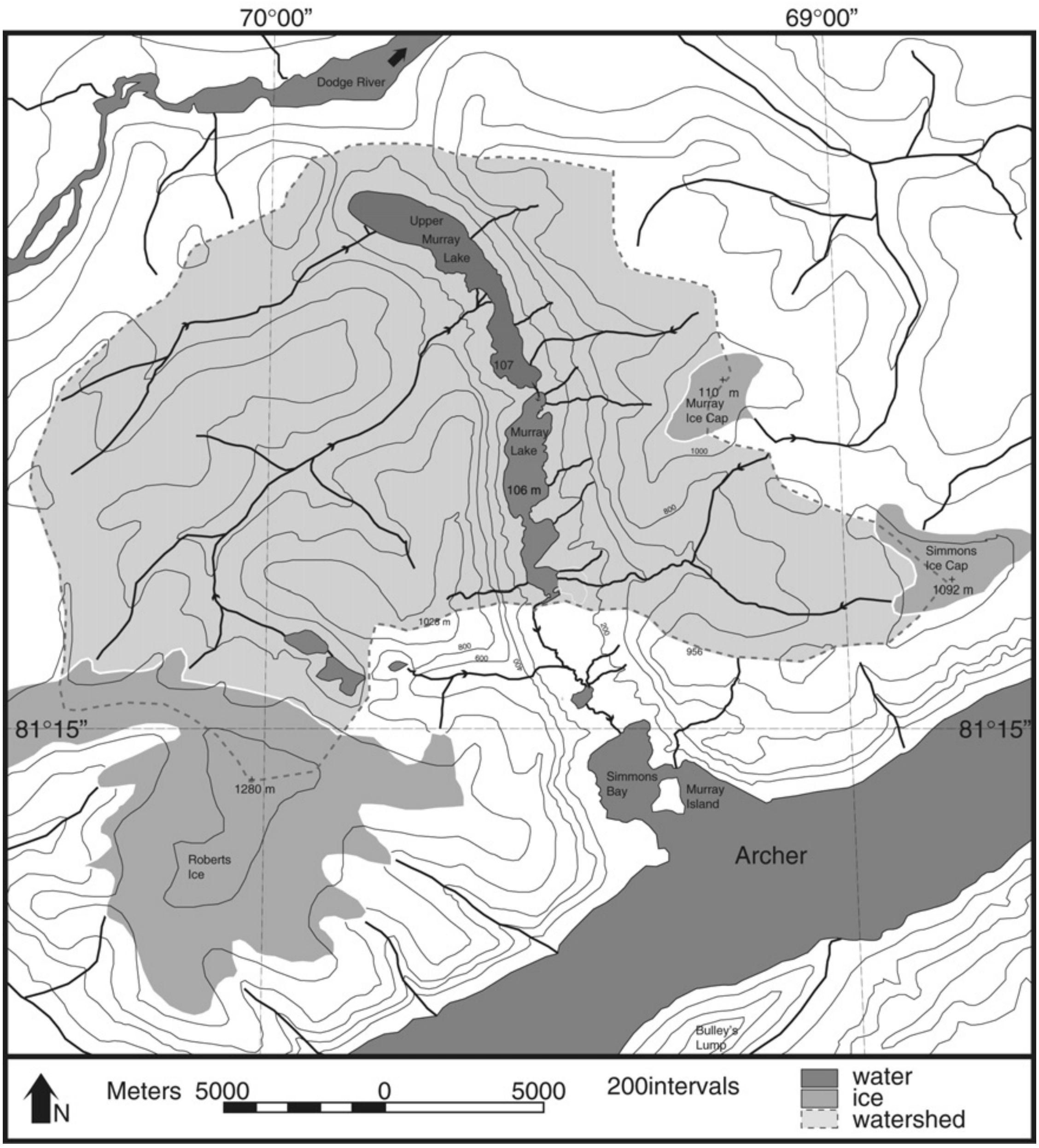

Figure 2 Map of the Murray Lakes watershed area (lightly shaded area). Ice caps are darkly shaded

LML is approximately the same size as UML, though the latter is much deeper in its northern basin (Table 1). Both are oligotrophic lakes with relatively uniform conditions in the water column, except for a strong gradient in the lowermost 5–10 m. In UML, there is strong stratification in the lowest ~8 m, with anoxic conditions at the sediment water interface (Figure 4). In LML, the lowest section of the water column has similar characteristics, but conditions are not completely anoxic at the present time. As discussed later, both the spatial and temporal distribution of anoxic conditions in the lake is critical in determining where varved sediments are preserved, and at what times. Changes in oxygenation at depth appear to be an important indicator of changing climatic conditions, and these can be tracked by documenting how varve preservation varies over time (cf. Lamoureux and Bradley, 1996).

Regional geological setting

The Hazen Plateau and Judge Daly Promontory, which lies to the southeast (Figure 1a), are mainly comprised of calcareous and dolomitic sandstone and mudrock of the Danish River Formation that originate from late Ordovician to early Silurian deep-water deposits (Trettin, 1989). There are also units of older sedimentary rocks such as late-Cambrian chert and re-sedimented carbonates that have been uplifted with the younger mudrock deposits. The sandstone and mudrock that make up the Murray Lakes watershed weathers and erodes readily and provides an ample source of calcareous and dolomitic sediments to be trapped in the lake basins.

Weathered bedrock/colluvium is the most common surficial unit that surrounds the lake basins and the valley floors. The sandstone and mudstone deepwater formations are easily weathered by active gelifluction processes, and colluvium makes up the top 1–2 m of the lithology on the surface of the bedrock. On lower gradient slopes there are flow deposits of coarse colluvium. Bedrock tends to be more exposed on the valley faces and on prominent ridges on the eastern rim of the plateau where extreme erosion and glacial plucking has occurred. On the upland areas of the plateau, the primary surficial units are blanket and veneer tills deposited during past glaciations.

Regional climatic setting and vegetation

The Murray Lakes experience a polar desert climate (Bovis and Barry, 1974) with a mean annual precipitation of less than 150 mm

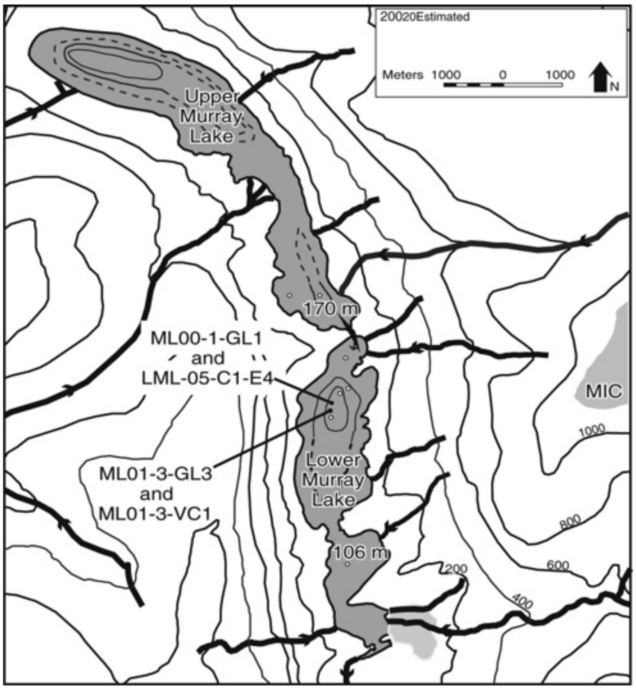

Figure 3 Bathymetric map of Upper and Lower Murray Lakes, with coring locations mentioned in text indicated by black dots. White dots indicate other coring locations that are not discussed within the text

(water equivalent) and a mean annual temperature of −20°C. There is complete darkness for four winter months and four months of 24-h sunlight from May through August. In the winter, persistent temperature inversions and cold air drainage lead to temperatures that locally drop below −40°C (Maxwell, 1980). However, in the brief summer months (June–August) the Hazen Plateau is a 'thermal oasis'; temperatures increase rapidly, with daily averages generally exceeding 0°C from early June until mid to late August, and daily maxima occasionally reaching ~18°C. Edlund and Alt (1989) characterize the interior of Ellesmere as having the highest summer temperatures and the lowest cloud cover of any of the islands in the High Arctic. This contrasts with the north coast of Ellesmere Island (where the nearest long meteorological record (~55 years) is available, at Alert (82.5°N, 62.3°W), ~180 km away) where low cloud and fog from the adjacent Arctic Ocean commonly limits summer temperatures. The only other long-term (~55 year) station record is from Eureka (80.0°N, 85.9°W; ~325 km from the Murray Lakes). However, Eureka may not be representative of regional conditions; it is in an interior continental location, and records the lowest annual precipitation of any of the synoptic weather stations in the Arctic owing to the effect of barrier mountains on Axel Heiberg Island to the west and the Grant Land Mountains to the north (Maxwell, 1981).

The plateau region adjacent to the Murray Lakes is one of the most densely and diversely vegetated regions of the Arctic (Edlund and Alt, 1989). In the Murray Lakes catchment vascular plants are relatively abundant. Arctic willow and arctic poppy are found in upland areas where the soil is moderately drained, and in the bottom regions of the catchment, where the soil is less well-drained, there are higher densities of grasses, sedges and purple saxifrage. On the shallow lake shores, there is an abundance of aquatic moss (*Drepanocladus* and *Scorpidium* spp.) and aquatic plants.

Table 1 Physiographic data for the Murray Lakes

Lake	Elevation (m)	Area (km^2)	Max. depth (m)	Watershed area (km^2)	% Glacierized
LML	106	6	47	45	5.3
UML	107	8.5	83	194	7.5

Methods

Sediment core recovery

Multiple sediment cores were recovered from the deepest basin of LML with a Rossfelder submersible vibracorer and Glew gravity corer in 2000 and 2001, and with an Ekman grab sampler in 2005. In this report, we focus primarily on the finely laminated sediments contained in Glew gravity cores ML00-1-GL1 (recovered from 47 m water depth at 81.3334°N, 69.54216°W) and (for palaeomagnetic analysis) ML01-3-GL3, another Glew core taken ~80 m away from ML00-1-GL1, in ~45 m water depth (Figure 3). The Ekman dredge samples (subsampled in core LML-05-C1-E4) were recovered from 46.13 m water depth at approximately the

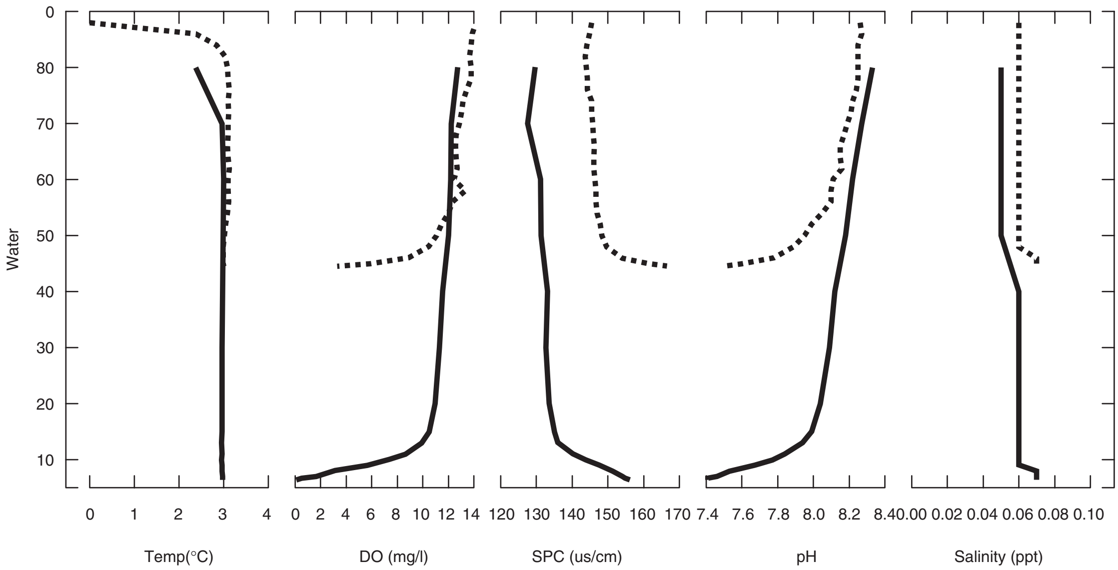

Figure 4 Water column profiles from LML (~45 m depth) and UML (~85 m depth), taken in early June 2005

same location as ML00-1-GL1 to provide ~15–20 cm of continuous laminated sediment up to the active sediment/water interface.

Core logging and analysis of physical sediment properties

We report here on laboratory analyses of cores ML00-1-GL1 and LML-05-C1-E4, and the palaeomagnetic properties of core ML01-3-GL3. A report on a longer vibracore (ML01-3-VC1) is in preparation. Cores were split, photographed and the magnetic properties of the sediments were measured in u-channels removed from the cores.

Radiocarbon dating

Organic matter is very sparse within the highly clastic sediments of LML. Four small fragments (≤ 1 mm) of woody plant material of terrestrial origin were picked from sediments in the long core ML01-3-VC1.

^{210}Pb and ^{137}Cs dating

The most recently deposited sediments were subsampled for ^{210}Pb and ^{137}Cs analysis by slicing 0.5 cm sections of the top 10 cm of sediment from a quarter section of core ML00-1-GL1. Owing to cost constraints, only the top 2.5cm (five samples) of sediment were analysed. Six additional measurements were taken from samples below 2.5 cm.

Sediment impregnation and varve chronology construction

The LML sediments are varved (ie, annually laminated), as discussed below. To facilitate the construction of a varve chronology, sediment was impregnated with resin in a manner similar to that described by Lamoureux (1994) and Francus and Asikainen (2001). First, sediment slabs were subsampled from split core halves using aluminum trays (18 cm × 2 cm × 0.7 cm). Trays were overlapped by at least 1.5 cm to ensure a continuous stratigraphic sequence. The trays were then flash-frozen in liquid nitrogen, dehydrated by freeze drying, and then impregnated under vacuum with Spurr's four component epoxy resin. After oven curing at 60°C for 12 h, the impregnated sediment slabs were cut into three sub-blocks (roughly 6 cm long) at an angle across the laminae to ensure that none of the sequence was lost because of the width of the cutting blade. Full size (2.5 cm × 7.5 cm), polished thin sections were then prepared from the sub-blocks.

High resolution (1440 dpi), plain transmitted light images were captured of each thin section with an Agfa DuoScan flatbed scanner and stored in Adobe Photoshop 5.5 format. Using a paths layer, a reference line was drawn vertically on each image and varves were delimited by tick marks perpendicular to the reference line at the culmination of each representative annual layer or the stratigraphic top of each clay cap. The path layers with varve markings were exported using Photoshop's 'Export→Paths to Illustrator …' function, and the results were run through a Microsoft Excel macro (Francus *et al*., 2002a), which calculated actual depths and thicknesses for each varve. Each thin section was counted and measured in this way twice in order to assess reproducibility of the varve counts, as well as to develop an accurate measurement of thickness for each varve. These two counts were later revised into a final third count when high resolution back-scattered electron imagery became available and problematic sections could be examined in more detail.

BSE image analysis

To characterize the microstructural and textural parameters of the varved sediments, quantitative image analysis was carried out on high resolution back-scattered electron (BSE) images of the varved sediments from ML00-1-GL1. After carbon coating the polished thin sections, the BSE imagery was acquired using a JEOL JSM-5410 Scanning Electron Microscope (SEM) set with a 20 kV beam accelerating voltage, a working distance of 20 mm, a spot size of 20 μm and a magnification of 100×. The region of interest (ROI) for each varve was defined as the region that represented the onset of sedimentation for a given year or the region that was stratigraphically above the clay cap. Images were captured at 1280 × 960 pixel resolution using a 4pi™ system, and processed using *NIH Image* v.1.61 (developed at the US National Institutes of Health and available at http://rsb.info.nih.gov/nih-image/, last accessed 19 October 2007).

Results and discussion

General core sedimentology and stratigraphy

Core ML00-1-GL1 consists of brownish/grey silty-clay (5Y 5/2) layers capped by either thin layers of grey clay (5Y 6/1) or thicker layers of dark grey clay (5Y 2.5/2). These visibly distinct silt/clay couplets are consistently fine (< 1 mm thick) and dominate the sequence except within the uppermost 3.4 cm as discussed below. The laminated stratigraphy is intermittently interrupted by thicker units of silty-sand. These units grade upwards from coarse sand to fine clay within a continuous sequence, indicating that they were deposited as one event, such as a turbidite or slumping event. Small fragments of organic debris were found in the thick turbidite at 35.5 cm depth. The uppermost 3.4 cm of ML00-1-GL1 are not finely laminated like the rest of the sequence. Some laminae with diffuse boundaries exist, but in several cases they are abruptly truncated, perhaps because this zone was disturbed during core recovery and/or shipment, though it is also possible that this zone may reflect real changes in local anoxia, as discussed further below. A clear bioturbated/pelletized texture is present in a 0.5 cm thick band of this section. A large turbidite is also visible towards the top of the sequence, but the remainder of the material is characterized by larger units of homogenized sediment that can be recognized based on colour variations. In 2005 an Ekman core (LML-05-C1-E4) was recovered to investigate further the section that may have been disturbed in ML00-1-GL1; in this new core, undisturbed varves were observed to the top of the deposit.

Core ML01-3-GL3 (54 cm long) was taken in the same manner as cores ML00-1-GL1, but at a slightly shallower water depth (45 m). Interestingly, the occurrence of laminations in this core is sporadic with clear, recognizable silt and clay couplets only from 3 to 15 cm depth and more homogenized silt and clay units above and below. However, the laminated section of ML01-3-GL3 does show a strong visual correlation with marker beds identified in ML00-1-GL1, and the homogenized section is similar to the upper ~3.4 cm of ML00-1-GL1. This suggests that the anoxic (or suboxic) conditions that are necessary for the preservation of laminations do not necessarily always exist basin-wide, but may be confined at times to small depressions within the general bathymetry of the lake bottom. This issue is discussed more extensively below.

Varve counts and chronology

A composite sequence was established using ML00-1-GL1 and LML-05-C1-E4 to cover the longest available undisturbed 55.75 cm section. Initial varve counts, along different counting transects on the thin sections, revealed 859 and 912 varves. A final varve count, produced after acquiring BSE images of each varve, revealed 972 varves, indicating an initial underestimation error of up to ~13%. Most of this counting error came from the middle to upper section of the sequence where the sedimentation was particularly low and laminations were sometimes difficult to clearly identify.

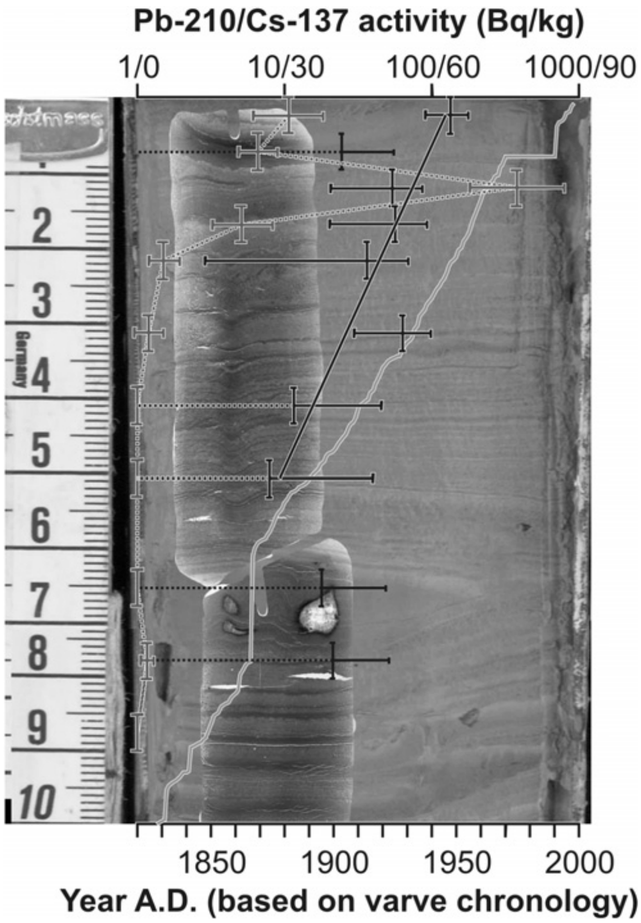

Figure 5 ^{210}Pb (black) and ^{137}Cs (medium grey) radiometric activity levels (upper axis) and varve-based age–depth model (light grey) superimposed on the ML00-1-GL1 sediments. Note that the ^{137}Cs data are plotted on a normal scale, and the ^{210}Pb data are plotted on a logarithmic scale. The best fit line is shown for the seven ^{210}Pb data points. The three black data points without white outlines are the three ^{210}Pb data points that were excluded from interpretation because they came from turbidite deposits. The two turbidites and erosion event can be clearly seen in the varve-based age–depth model curve

A number of silt-sand units appeared to be turbidites, though only one showed clear evidence of an erosive lower boundary (as seen in both the Ekman sediments and in the Glew core). This was at ~1.5 cm depth in the Ekman, ie, ~15 varve years below the surface (~AD 1990). We estimate ~20 varves were removed based on the ^{137}Cs record, which provides a guide as discussed below. On that basis, the varve record spans the period AD 1013–2004.

Dating analyses and the varve chronology

Of the four woody plant samples of terrestrial origin that were sampled from the sediment cores, all were highly fragmented and showed scarring patterns, which suggests they had experienced abundant reworking in the watershed prior to being washed into the lake where they were deposited. Two of the samples (81.75 cm and 158.6 cm depth in core ML01-3-VC1) were too small for analysis. The sample from 31.25 cm depth in core ML01-3-VC1 was picked from a 1.5 cm thick, well-graded turbidite and produced a ^{14}C age of 1640±30 yr BP (calibrated age: 1533 yr BP). This compares with an age of only 618 yr BP, based on the counting of varves. The sample taken from 448.75 cm in core ML01-3-VC1 returned a ^{14}C age of 46 100 ± 770 years. This date is far too old for the sedimentary setting and suggests that it may, in fact, be Tertiary wood that is occasionally found in the area. The discrepancies between the ^{14}C ages and varve chronology ages is not surprising given that the samples showed evidence of reworking before final deposition.

The results of the ^{210}Pb and ^{137}Cs analysis are presented in Figure 5, which shows the activity levels superimposed on an image of the top section of the short core. The problem with developing an accurate ^{210}Pb-based chronology for the upper sediments is the low flux rate of the radionuclides to the lake. This can be seen in the very low activities of total ^{210}Pb measured in the 0.5 cm samples (<100 Bq/kg below top sample). The calculated unsupported values of ^{210}Pb (^{210}Pb in excess of background values) show low levels of activity (< 70 Bq/kg) and high error values (> 50% of the measured value). These low values are typical of Arctic ^{210}Pb flux rates, which are much lower than those over northern continental land masses (Hermanson, 1990). The low radionuclide concentrations that are found in lake sediments are due to a combination of low atmospheric fallout because of suppression of the parent isotope ^{222}Rn in permafrost and prolonged ice cover, which prohibits direct deposition except during the summer ice-free months (Hermanson, 1990). As a result, the transportation of radionuclides into arctic lakes rests on a number of processes, including streamflow and aeolian input. Because arctic lakes derive more radionuclide input from transport mechanisms other than direct precipitation there are complications in interpreting activity levels, because discharge and groundwater inputs vary. Unpredictable depositional events such as high discharge events or slump deposits tend to create further problems of radionuclide dilution. The variable input of ^{210}Pb in LML, as indicated by the lack of a consistent activity curve in the sediments, as well as the high error values, can probably be explained by a combination of mixing in the upper sediments and turbidite events. Error values of the upper LML sediments are especially high for the upper six ^{210}Pb values and there are significant variations in activity levels in the sand layers that have been identified as turbidites at depths of 0.5 cm and 7 cm (Figure 5). If the three ^{210}Pb measurements that were taken from turbidite layers (0.5, 6.5 and 7.5 cm depth – see the grey-shaded data points in Figure 5) are eliminated from the radionuclide profile the activity levels then exhibit a more constant rate of decay. A sedimentation rate of 0.052 cm/yr is calculated with this decay curve, which closely matches the mean sedimentation rate of 0.057 cm/yr determined from the varve count on the complete 55.75 cm composite sequence.

The artificial radionuclide ^{137}Cs shows measured activities with a well-defined peak (at 77 ± 10 Bq/kg) in sample 3 (1–1.5 cm depth) in core ML00-1-GL1. The period of atmospheric nuclear weapons testing began in 1952 and reached significant levels in the atmosphere in 1954. Following a brief moratorium of testing in 1958, the fallout increased globally from 1961 to 1963, with highest levels reached in 1963 before the practice was banned. The LML sediments do not show this two-peak pattern, because of a lack of resolution with the large (0.5 cm) sampling interval. The 0.5 cm thick zone represented by sample 3 with the ^{137}Cs peak corresponds to varve years 1980–1988 if the varve chronology is assumed to be continuous. However, as mentioned above, the prominent turbidite event recorded in the 1990 varve was clearly erosive. Thus, assuming the ^{137}Cs peak in sample 3 represents ~1963, if we take the centre of the 0.5 cm zone as 1963, it suggests that the varves from ~1970 to 1989 inclusive were eroded by the 1990 turbidite. We note that this is problematical for calibration purposes, as almost half of the period for which there are instrumental data is unrepresented in the varve record.

In summary, the radiocarbon dates obtained are far too old and do not agree with varve counts; we interpret this to mean the material dated was reworked or redeposited old material. We have found similar discrepancies in all of the High Arctic lakes with varved sediments that we have examined. The ^{210}Pb decay curve yields a calculated sedimentation rate of 0.052 cm/yr, which

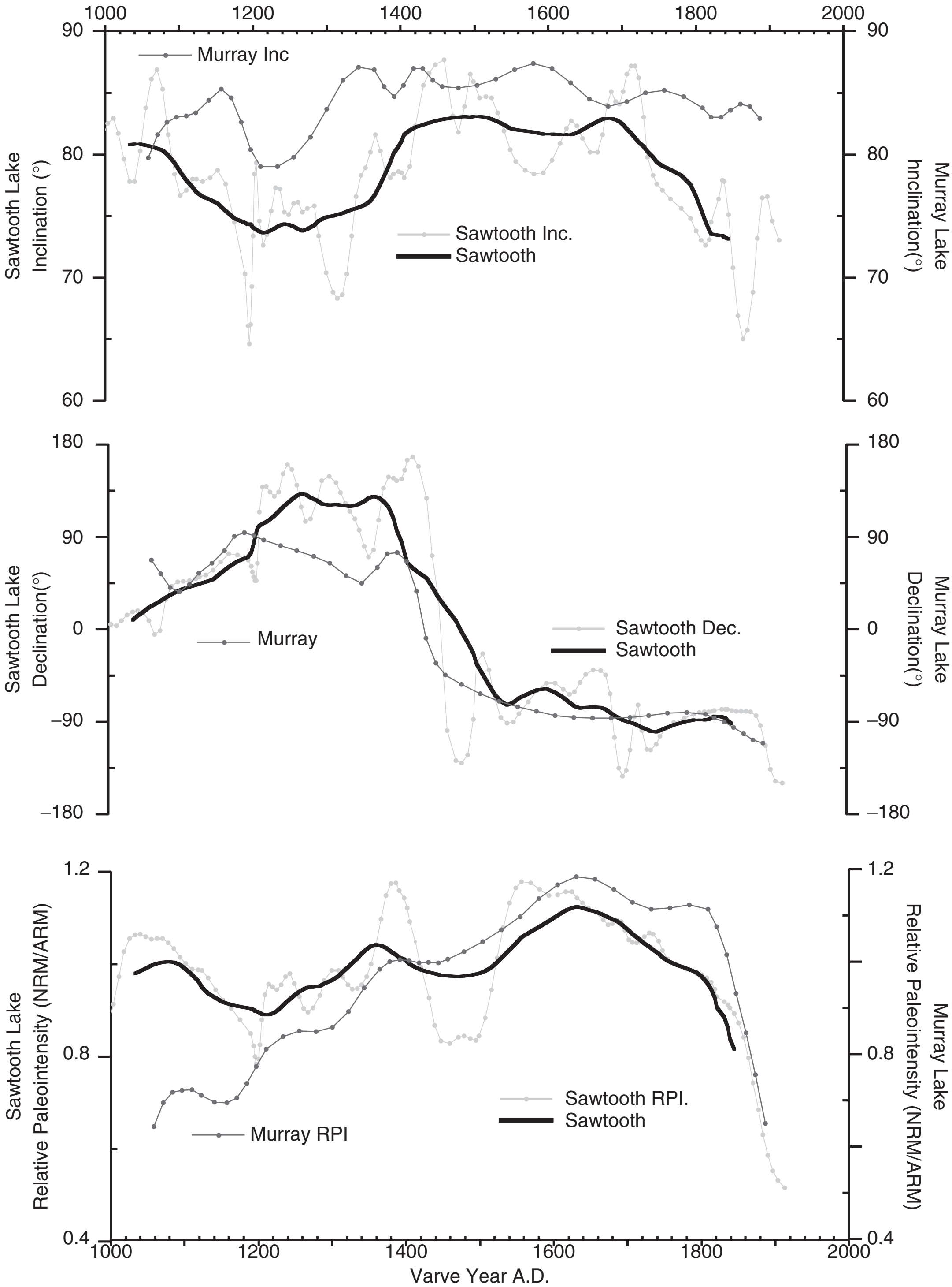

Figure 6 Palaeomagnetic secular variation (inclination, declination and relative palaeointensity) records from Sawtooth Lake (light grey line, raw; black line, 20 cm running mean) and Lower Murray Lake (medium grey line), Ellesmere Island on their independently derived varve-based chronologies. Upper panel: the characteristic remanent magnetization (ChRM) calculated from the 20 through 80 mT demagnetization steps, inclination. Middle panel: the ChRM declination, calibrated to the historical record. Lower panel: relative palaeointensity, calculated from the mean of the NRM/ARM ratio from the 10 through 60 mT demagnetization steps. The higher frequency variations in the Sawtooth Lake records (light grey) were smoothed using a 20 cm running mean (black line) to better reflect the lower accumulation rate of the Murray Lake record and to reduce depositional noise

shows good agreement with the long-term calculated sedimentation rate of 0.057 cm/yr according to the varve chronology. The ^{137}Cs data are consistent with the varve chronology, after accounting for erosive action of the 1990 turbidite layer, which may have removed ~20 varves from the sediment pile.

Sedimentation patterns are consistent with our expectation that the observed laminations are annual (varved) couplets (fining upwards, with clay caps), reflecting the strong annual cycle of sedimentation that prevails in the lake. We also observed that five complete additional laminations were present in cores from early in 2005 compared with those from 2000, which supports our interpretation of annual deposition. However, we recognize that these observations are necessary, but not sufficient, criteria on which to base a chronology. We therefore compared the palaeomagnetic

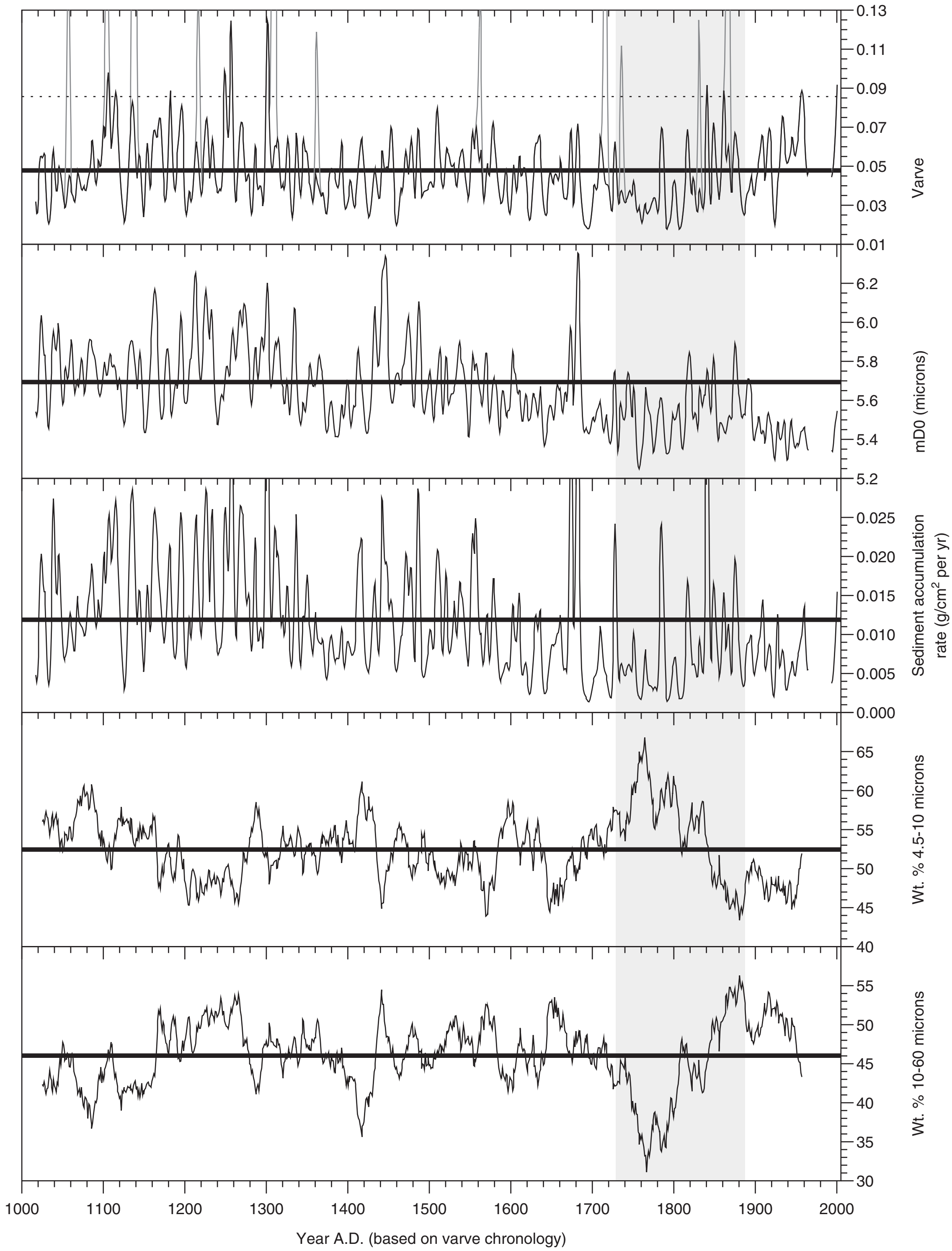

Figure 7 Sedimentological indices measured on individual varves in core ML00-1-GL1 and Ekman core LML-05-C1-E4; thick black horizontal lines indicate mean values for the period of record. Light shaded period indicates the interval in the last millennium that is considered to be the culmination of the most recent episode of Neoglaciation in the region, as discussed in the text: panel 1, top: varve thickness. Grey curve shows 9-year Gaussian filtered record; black curve shows the same, but 13 turbidites were replaced with the period average thickness. Dotted line shows the filtered mean value for the year last 9 years. Panel 2: median grain size (mD_0 in μm) from BSE image analysis of individual varves. Panel 3: estimated sediment flux, based on varve thickness adjusted for % packing, and assuming a constant sediment density of 2.65 g/cm^3, for quartz. Panel 4: percentage of grains in the 4.5–10 μm range. Panel 5: percentage of grains in the10–60 μm range

characteristics of the LML sedimentary record in ML01-3-GL3 with another independently derived varve chronology (from core SS99-10-1 from Sawtooth Lake, ~380 km to the southwest) to assess the veracity of our timescale. A comparison of palaeomagnetic records from the two sites provides a powerful test of the two independently derived chronologies over a common time interval (Figure 6). Bearing in mind that each lake has a different sedimentation rate (Sawtooth record of 143 cm versus 55.75 cm in LML), different sediment characteristics and palaeomagnetic properties, and the palaeomagnetic signal is integrated over several centimetres of each core (cf. Stoner, J.S., St-Onge, G., Francus, P., Bradley, R.S., Abbott, M., Verosub, K.L. and

Channell, J.E.T., unpublished data, 2007), there are nevertheless strong correlations in declination and palaeointensity, and to a lesser extent in inclination throughout the two sequences. The matches of these magnetic parameters confirm that the two chronologies, established independently by varve counting, are consistent for the last millennium and we interpret this as evidence that the chronologies based on varve counting are reasonably accurate over that time interval. However, at present it is not possible to fully quantify the level of uncertainty in the LML chronology; additional cores with annual resolution will be needed to further reduce sources of error resulting from sediment disturbances, thin/missed layers, localized slumping events or erosion by turbidite events. If additional chronological markers can be identified (such as tephra shards of known age) this will greatly improve varve chronologies from the High Arctic, where reliable radiocarbon dating has proven to be extremely difficult.

Sediment image analysis

Noise in the BSE images was removed with filters (median filter, contrast kernel and hybrid median filter), and then a threshold value that fitted the contrast and brightness for each particular image was chosen. Next, a binary image was produced, with a quality that was improved by a number of operations including dilating/eroding, filling interior holes in the objects, removing less than 15-pixel objects and separating touching objects (cf. Francus, 1998; Soreghan and Francus, 2004). Finally, a processed black and white image of the sediment grains within a varve was produced. These images became the basis for the calculation of several sedimentary indices, including grain diameter and grain area, using a minimum particle size threshold of 4.5 μm. The size fraction < 4.5 μm includes fine clays that compose the background sediment matrix for the varves. On average, each image contained ~1100 grains, which were individually measured for grain size using the apparent disc diameter (D_0) and the different relative size fractions were computed for each image. Figure 7 shows some of these indices, for the last ~1000 years.

The varve thickness plot shows that the thickest varves were deposited from ~AD 1100 to the early 1300s in LML. This section of the series also has a relatively higher median grain size than later parts of the record, which we interpret as the result of more energy available (via streamflow) to transport somewhat larger sized material. Minimum varve thickness was in the eighteenth and early nineteenth centuries, after which varve thickness increased to the present, and varve thicknesses in recent years have been in the highest (> 95th) percentile range of the entire record. On the other hand, because of compaction, the thickness of recent varves is not directly comparable with those varves that are buried deeper in the sediment pile. This problem can be addressed by calculating a packing index (a simple ratio of the area occupied by sediment grains versus the area occupied by matrix in the varve BSE images) and then calculating the sediment accumulation rate on an annual basis (assuming a constant sediment density of 2.65 g/cm^3, for quartz). This procedure compensates for compression of the sediment with depth, and results in a suppression of the trend over the last century seen in the varve thickness record (Figure 7). Sediment accumulation rate was clearly lowest in the eighteenth and early nineteenth centuries, as observed in the varve thickness record, but the sediment accumulation rate record does not support the conclusion that twentieth-century changes are comparable with those of the twelfth to fourteenth centuries in LML. This comparison of the calculated sediment accumulation rate and varve thickness series points to an important issue that is not commonly addressed in varve studies: how should changes in downcore compression (density) be taken into account? Usually, discrete samples of dry bulk density (commonly 1 cm^3 samples) are measured down a sediment core, which provides only a crude measure of changes in varve sediment density. Image analysis offers the opportunity to measure the packing of particles directly on a varve by varve basis, but even this procedure is complicated by changes in grain size and shape over time. Further studies of this matter are required because the very issue of how modern sedimentation compares with sediment deposition in the past is critically dependent on how the data are adjusted, as Figure 7 readily shows.

It is notable that a remarkable change in diatoms was observed in the uppermost ~0.75 cm of sediment. No diatoms were found in the sediments until at 0.75 cm depth the littoral species *Campylodiscus* (most likely, sp. *noricus*) makes a sudden first appearance in the 1998 varve and increases to profuse quantities (up to ~40 frustules per 0.01 cm^2 in BSE imagery) by the end of the record just 6 varve years later. We find no evidence that this sudden appearance is related to dissolution downcore. *Campylodiscus* has been seen as an early indicator of warming in many large High Arctic lakes (B. Perren, personal communication, 2007), so LML seems to be at a threshold in its ontogenetic development towards a more diverse and extensive lacustrine flora. This is consistent with a number of other studies of lakes from the High Arctic (Smol and Douglas, 2007) and from other parts of the Arctic (Smol *et al*., 2005).

The lower panel in Figure 7 details the down-core changes in the grain size fraction, as percentages. Approximately half of the measured sediment matrix is composed of very small grain sizes (< 10 μm) with most of the sediment fraction in the fine silt to silt fraction. Only rarely does sand-size material reach the site, probably via ice-rafting or underflows (cf. Francus *et al*., 2008). A comparison of the 4.5–10 μm and the 10–60 μm fractions shows that more coarse material was transported to the deepest part of the lake in the early centuries of this record whereas in the eighteenth and early nineteenth centuries, finer sized particles were especially abundant. We interpret this as an indication that warmer conditions prevailed in the early centuries of the last millennium, resulting in more runoff and associated energy available for transporting material, followed by colder conditions, which culminated in the eighteenth and nineteenth centuries.

Varve preservation in LML

Although a number of cores were acquired from the deep basin of LML, it was found that only cores from the very deepest zones (ie, the 2000 Glew cores retrieved from 47 m water depth, and the 2005 Ekman core retrieved from 46.13 m water depth) consistently preserved the annual laminae. Cores taken in relatively close proximity (within ~100 m) but slightly shallower water depth ~45 m) did not show a continuous sequence of the fine sediment structures to allow the construction of a varve chronology. Cores taken from a water depth of 40 m or less showed no preservation of sediment layers. This intermittent varve preservation suggests that water column stratification in the lake fluctuates and continuous varve preservation is, therefore limited to only the very deepest part of the basin (below 45 m). This has been observed elsewhere (Francus *et al*., 2008). Water column profiles taken in 2005 show that although the water column had low oxygen levels in the lowest ~2–3 m (< 5 mg/l) conditions were suboxic at the sediment–water interface; this may explain the poor preservation of varves in the uppermost 3.4 cm of the Glew cores from 2000. This suggests that completely anoxic conditions may not have been present for several decades, even in deep parts of the basin. This may reflect more open-water conditions, and/or more runoff, which may have led to oxygenation of the deepest waters. In fact, the presence or absence of varves can be viewed as a consequence of such changes, and thus indicative of past (summer) climatic conditions. We thus correlated the intermittent varve record from the core at 45 m water depth with the continuous records from 47 m, using marker beds from the well preserved deeper cores.

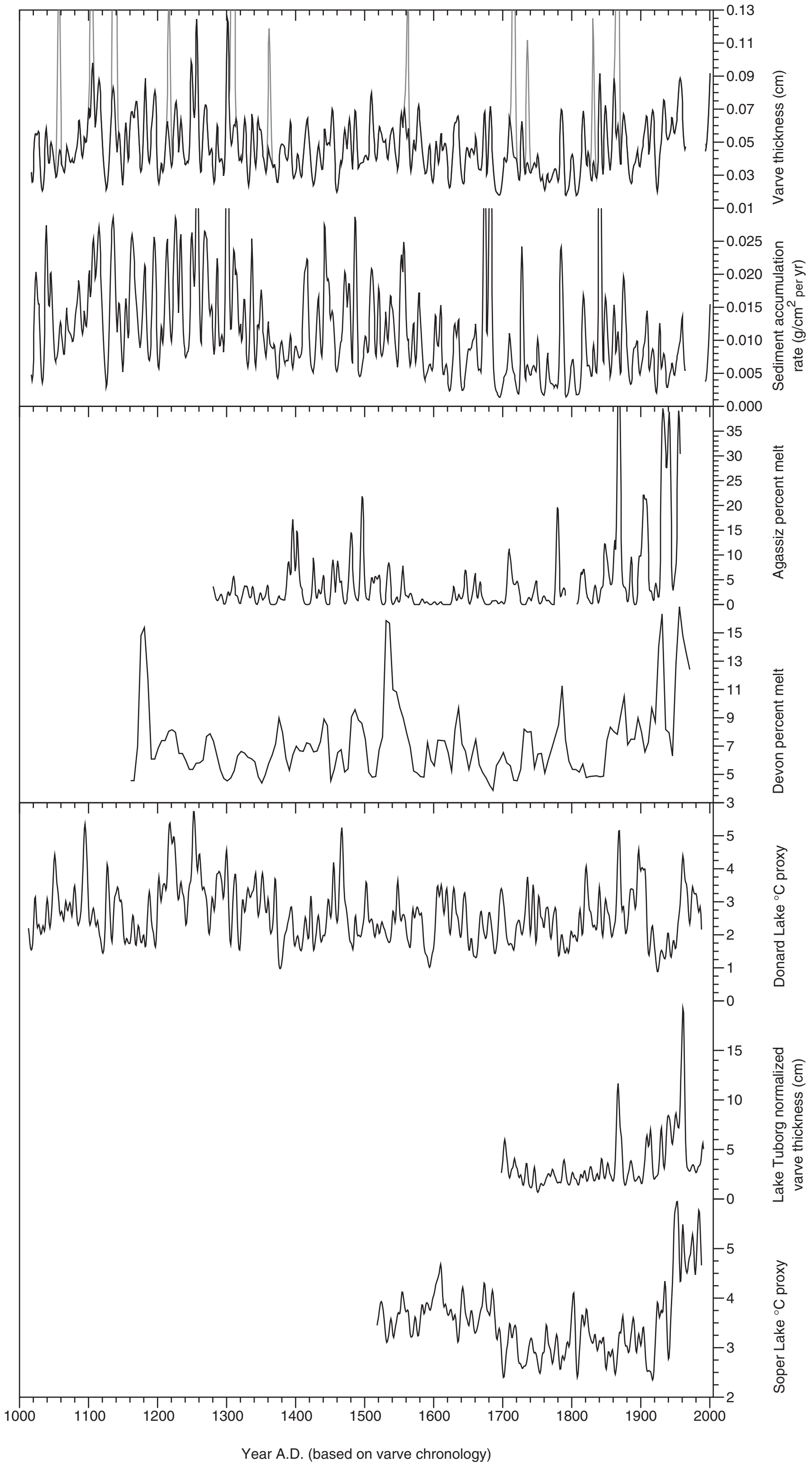

Figure 8 Upper panel: LML varve thickness and estimated sediment flux; middle panel: Agassiz Ice Cap and Devon Island Ice Cap melt percent record (Koerner, 1977; Fisher and Koerner, 1994); lower panel: summer temperature reconstructions from southern Baffin Island (Donard and Soper Lakes; Moore *et al*., 2001 and Hughen *et al*., 2000, respectively) based on varve thickness, and varve thickness record from Lake Tuborg, Ellesmere Island (Smith *et al*., 2004)

Varve preservation was found to be poor from the bottom of the core (taken from 45 m water depth) until varve year 1686. From 1686 to 1698 varves were discernible but diffuse before the varves were disturbed again (1699 to 1728). From 1729 to 1887 varves were well preserved and consistently match the 2000 cores. Between 1888 and 1902 the varves deteriorate and above 1920 they are appear to be completely absent.

The intervals when varves are well preserved in both 45 and 47 m deep cores indicate periods of stronger density stratification in the lake. Thus, the lake was the most stable from AD 1729 to 1887 with approximately two decades of variability before and after. Lamoureux and Bradley (1996) observed a similar occurrence of alternating well-defined and diffuse varves during transitional intervals. Two possible explanations may account for the variation in the lake stratification, resulting in variable varve preservation.

(1) During periods of increased freshwater flux the oxycline would be depressed and varves would be disturbed by summer mixing and/or turbulence in the water column.
(2) During cold intervals lake ice cover would be more extensive in the summer, which would shield the lake from wind as well as prevent thermal mixing in the water column.

It is impossible to evaluate whether lake ice cover or freshwater flux has more of an impact on lake density stratification without a more detailed set of water column measurements and field observations. However, the processes are complementary and may work together to form a stable lake basin (ie, during cold periods lake ice would be more extensive and freshwater flux would be decreased). In either case, varve preservation is poor below 0.6 m in the cores from 45 m depth, suggesting that the period from 3 ka to ~AD 1700 was never as cold (and/or dry) as the latest Neoglacial episode. The stable interval, from AD 1729 to 1887 corresponds with the period in the record when varves were extremely thin, sediment accumulation rates were lowest and there was a higher abundance of fine particles (Figure 7). We consider this to be the culmination of the most recent episode of Neoglaciation in the region.

The LML varve/climate link

Previous studies from Ellesmere Island and other locations in the Canadian Arctic have demonstrated that varve thickness is related to summer (especially early summer) temperatures, when the melting of snowpack provides energy to transport material to the lakes (Hardy, 1996; Gajewski *et al*., 1997; Braun *et al*., 2000; Hughen *et al*., 2000; Moore *et al*., 2001; Francus *et al*., 2002b; Smith *et al*., 2004). Variations in winter snowfall (which is generally light in this polar desert environment) do not appear to be significant factors in sediment flux (Hardy *et al*., 1996). These conclusions are based on hydrological and sediment monitoring studies in several different lakes and although such studies were not carried out in the Murray Lakes watershed, similar controls on sediment flux certainly operate there. However, it is extremely difficult to quantitatively relate varve thickness, or other sedimentary characteristics, directly to meteorological data because the nearest long-term weather stations (Eureka and Alert) are 320 and 180 km from the lake, respectively, and the closer station is in a quite different meteorological setting (on the Arctic Ocean coast, where fog and low cloud are common in summer months). Furthermore, sediment erosion beneath the ~1990 turbidite (which we can only estimate as roughly 20 years) greatly limits comparison of the varves with regional meteorological data. We are thus constrained to simply hypothesize that the varve record represents summer temperature conditions in the Murray Lakes watershed, based on our observations and experience in similar settings. We can also assess the climatic implications of the LML varves, by comparing them with other proxy records, for which climate links have been suggested. Figure 8 shows two LML indices (varve thickness and sediment accumulation rate) compared with a diverse group of proxy records that reflect summer temperature in the arctic. The records are presented with a 9-yr Gaussian filter (except Devon Island ice core melt %) in order to compare the general patterns in the time series, recognizing the inherent chronological uncertainties in all the records. Most records show warmest conditions in the twentieth century, and cold conditions in the eighteenth and nineteenth centuries, in line with the LML varve thickness record. There is evidence for relatively warm conditions in the 1400s and 1500s (in LML sediment accumulation rate, Agassiz melt % and Soper Lake temperatures) and in the thirteenth century at Donard Lake (southern Baffin Island). The LML sediment accumulation rate and the Donard Lake varve-based temperature reconstruction each show this early warm interval as coming to an abrupt halt around ~AD 1375, with colder conditions in the late fourteenth /early fifteenth centuries. However, all proxy records are noisy, and their links to climate are generally poorly defined, in large part because of the severe limitations imposed by extremely sparse meteorological data.

Conclusions

A record of varve thickness, estimated sediment accumulation rate and various sedimentary parameters have been obtained on an annual basis for the last millennium, from Lower Murray Lake in the northern Canadian Arctic. Varves are generally very thin (<0.5 mm) and varve preservation changes through time, with only the deepest parts of the basin containing a continuous record. A completely accurate chronology is not possible because of difficulties in radiometric dating and recent erosion by a turbidite, but we estimate that the record is unlikely to have a cumulative error of more than 13% over the last millennium, and the real error is probably much smaller. A comparison of the palaeomagnetic properties of LML sediments with those from another High Arctic Lake, for which an entirely independent chronology was derived, shows good correspondence, indicating internal consistency between those records. Further improvements will require completely independent chronological verification, such as might be obtained from cryptotephra of known age. Furthermore, a quantitative climatic interpretation of the sedimentary characteristics is made difficult by limited meteorological data from the region, and by an erosive event that removed sediment deposited during the 1970s and 1980s. Nevertheless, fieldwork on other High Arctic lakes clearly indicates that sediment transport and varve thickness are related to temperatures during the short summer season that prevails in this region, and we have no reason to think that this is not the case for Lower Murray Lake. Comparisons with other proxies support our interpretation that conditions in the twelfth and thirteenth centuries were relatively warm, before turning cooler in the late fourteenth century. Coldest conditions of the last millennium prevailed in the eighteenth and early nineteenth centuries. Evidence for more recent warming is equivocal, with different interpretations possible depending on the parameter examined. Further improvements to quantitative palaeoclimate reconstructions in remote areas such as the Murray Lakes watershed are only likely through detailed process-based monitoring of hydrological and sedimentary processes over many years (cf. Hardy, 1996; Hardy *et al*., 1996; Braun *et al*., 2000; Gilbert and Lamoureux, 2004; Forbes and Lamoureux 2005). Such work is expensive and time-consuming, but nevertheless an essential complement to high-resolution studies of varve sediments in lakes from remote areas such as the High Arctic.

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