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A late Holocene varved sediment record of environmental change from northern Ellesmere Island, Canada *

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Abstract

A composite record of varve sedimentation is presented from high arctic meromictic Lake C2. The combination of a short runoff and sediment transport season with the strong density stratification of the lake lead to the formation of annual sediment couplets. This conclusion was confirmed by ^{210}Pb determinations. High intra-lake correlation of the varves allowed the construction of a composite record of varve sedimentation from overlapping segments of multiple sediment cores. Cross-dating between core segments isolated counting errors in individual cores, that could be attributed to minor sediment disturbances and vague structures. Resolving counting errors by cross-dating reduced the chronological error of the composite series to an estimated ±57 years.

The Lake C2 series is the first non-ice cap, high resolution late-Holocene environmental record from the Canadian high arctic. The composite varve series compares favorably with other high resolution proxies from the arctic, in particular with the ice core records from Devon Island and Camp Century, Greenland. A general correspondence between the varve record and other North American proxies for the little Ice Age period (1400–1900 AD) suggests that the Lake C2 record is sensitive to large-scale synoptic changes.

Introduction

Varved sediments formed in lacustrine and marine environments have long been recognized as a valuable geochronology tool and have been extensively studied and documented in North America and Europe (De Geer, 1912; Antevs, 1951; O'Sullivan, 1983; Smith & Ashley, 1985). In Sweden, nearly a century of work has produced a linked regional varve chronology spanning 12 500 years to the present (Boygle, 1993). The precise chronological control provided by the varved sediments has only recently been explored for reconstructing high-resolution records of past environments. Moreover, relatively few studies have attempted to determine a quantitative climate-varve relationship. Frequently, difficulties have arisen where the annual nature of the laminae was in question (e.g. Perkins & Sims, 1983; Cromack, 1991). Nevertheless, several studies from mid-latitude sites show the potential of calibrating climate to clastic varve thickness (Soutar & Crill, 1977; Leonard, 1985, 1986; Leemann & Niessen, 1994; Deslodges, 1994; Hughen *et al.*, 1995).

This paper reports the construction of a composite record of varved sedimentation from Lake C2 in the Canadian high arctic. Intensive limnological and hydrological studies during three melt seasons provide an unique and valuable database for relating varve thickness to climatic parameters, and detailed sedimentological studies confirm the presence of varves in the uppermost sediments from Lake C2 (Zolitschka, 1996). The varved record also provides a reference chronology for reconstructing paleoenvironmental change from other C2 sediment proxies (Douglas, 1996; Ludlam *et al.*, 1996b), and provides a high quality baseline dataset for studying future climate changes in the high arctic.

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* This is the tenth in a series of papers published in this issue on the Taconite Inlet Lakes Project. These papers were collected by Dr R. S. Bradley.

Study area

The Taconite Inlet project has been introduced by Bradley *et al.* (1996) and the reader is referred that work for details of the physical setting of Lake C2. Details regarding the process and monitoring studies undertaken during the 1990–92 melt seasons are described in separate papers as follows: hydroclimatology and sediment transport (Hardy, 1996), sediment routing and distribution (Retelle & Child, 1996), limnology (Ludlam, 1996a, b), and sedimentology (Zolitschka, 1996). Hardy *et al.* (1996) describe the relationship between climatic parameters and varve sedimentation rates for the Lake C2 watershed.

Methods

Field

Sediment cores were retrieved during the 1991 and 1992 field seasons from deep, gently sloping locations in the lake. Coring sites were chosen to observe changes in sediment depositional patterns throughout the lake, both above, and below the oxycline. Short sediment cores (<30 cm) with undisturbed surface sediments were taken with a percussion corer or an Ekman dredge. Dredge sediments were subsampled at the ice surface by pressing short lengths of core tubing into the sediment. Longer cores were retrieved utilizing a modified piston-percussion coring unit (Reasoner, 1993).

Laboratory

Prior to splitting, the magnetic susceptibility of the cores was measured with a Sapphire Instruments coil. The core tubes were cut with a saw and the sediments were split by running a fine wire down the length of the core. The exposed sediments were cleaned by running the edge of a razor blade parallel to the sediment structures to remove any disturbed sediment. Following cleaning, the sediments were visually logged, photographed, and x-rayed. Bulk and dry density, loss-on-ignition, and grain size distributions were measured at 2 cm intervals to characterize the sediment.

Detailed investigations of the varved sediments required the preparation of thin sections. Slabs of sediment were removed from cores for embedding in epoxy resin and thin sectioned utilizing previously described methods (Clark, 1988; Overpeck & Wagner, 1990). Changes to published embedding methods primarily related to the subsampling and handling of unfrozen lake sediments (Lamoureux, 1994a). Frozen sediments were considered inferior for the purposes of this study because ice-crystal growth disrupted sediment structures, making identification of fine sedimentary structures difficult. The method employed shallow metal trays (11 × 2 × 0.75 cm) pressed into the sediment in an overlapping arrangement to assure that a continuous record was obtained from each core. The samples were removed from the core, dehydrated with repeated applications of acetone, and embedded with Spurr low-viscosity epoxy resin (Lamoureux, 1994a). The embedded sediment samples were cured and thin-sectioned by a commercial laboratory. After receiving the thin sections, detailed photomicrographs were taken for archiving. Attempts to x-ray the thin sections were unsuccessful due to poor contrast between the sediment and the glass slide.

Varve counting and measurement

Sediment cores with clearly defined laminae and exhibiting minimal disturbance were selected for counting and measurement in this study. Laminae in sediments from cores above the oxycline were diffuse, making delineation of fine structures impossible, and were excluded.

Initially, the thin sections were visually inspected on a light table to identify distinctive marker beds in the cores. Prominent thick and/or dark beds that were clearly visible without magnification were selected as marker beds. The marker beds were chosen at approximately 2 cm intervals, confirmed by microscopic inspection, described, and labeled on each thin section. The marker beds were used as limits for counting and measuring intervals, and were intended to provide a means of comparing results from short sections (cf. Sprowl, 1993).

Counting and measuring of the varves was carried out on a Laborlux 11 POL monocular microscope under normal and polarized light. Counting and measuring practice was similar to that used by Zolitschka (1996). The varves between each marker bed were counted in three consecutive passes, each taken along a single vertical axis of the thin section, usually the left, center and right-hand sides. Where a disturbance occurred on one axis, an adjoining axis was counted to provide continuity. If the entire horizontal extent of the thin section was disturbed, the associated marker bed sequence was not counted or measured for that core.

Measurements were taken with the microscope eyepiece graticule, calibrated by a stage micrometer. Measurements were taken in an identical manner to the counting phase along a single axis. Because the count from each axis varied, measurements were taken from the axis with the highest total, which usually represented the axis with the least disturbance. The recorded thickness was the mean of three measurements from the field of view. Where significant variability in thickness was noted, the measurement recorded was the mean of the visible maximum and minimum.

Cross-dating and correlating varve series

Discrepancies between core segments were resolved by identifying units that were recognized in one core and not another. Potentially, discrepancies could result from either localized sedimentation that did not produce a lake-wide couplet or because an error was introduced during measurement. Given that repeated counts of a core segment frequently resulted in different results (Zolitschka, 1996; Sprowl, 1993), the potential for such an error is very real. In the simplest case with two core series, three types of error could occur. Errors would result where varves were either missed (Type A) or falsely identified (Type B). In both cases, the error may be due to the disturbance of the sediment, vague structures, operator inexperience or inconsistent techniques. The third type of error (Type C) would occur when a varve was missed in all cores investigated. Examining multiple sediment cores would likely reduce the probability of Type C errors.

Marker beds represented known stratigraphic horizons and allowed the identification and resolution of discrepancies on short sequences of varve measurements. Individual measurements were compared to identify significant differences in thickness, and relevant portions of the thin sections were reviewed to determine whether a varve was missed or incorrectly identified. This process was repeated until each varve in the marker bed sequence was correlated pair-wise with the other cores.

High amplitude noise caused by couplets several orders of magnitude thicker than the series mean was relatively common in the raw measurement data series. Similar examples of sporadic high amplitude noise occur in other paleoclimatic data sets and are isolated and treated with a variety of multivariate statistical techniques (Mayewski *et al.*, 1993). Based on our observations of varve sedimentation in the lake, the very thick units were considered to be non-climatic in origin (Retelle & Child, 1996). In most cases these units showed evidence of grading, suggesting that they were produced by turbidites. On the basis of this reasoning, we would argue that removing the high amplitude noise introduced into the measurement series by the turbidites was appropriate. Suspected turbidites were replaced with the series mean to maintain the varve chronology. This step was justified as all units replaced were capped by a winter clay unit.

Several methods were used to identify trends in varve thickness and variability. The primary method used a Gaussian smoothing of the data files to reduce the high frequency noise and to help differentiate between extended periods of high and low sedimentation. The sensitivity of the data was measured with a statistic used by dendroclimatologists referred to as the average mean sensitivity (ms_x) and defined as follows (Fritts, 1976):

$$\mathrm{ms}_x = \frac{1}{n-1} \sum_{t=1}^{t=n-1} \left| \frac{2(x_{t+1} - x_t)}{x_{t+1} + x_t} \right|$$

where x_t and x_{t+1} represent consecutive varve thickness measurements. The mean sensitivity measures the average difference between adjacent data points and can be interpreted as an estimate of the sensitivity between successive years in the data set. Varve data exhibiting low sensitivity (0) would show relatively low inter-annual variation and higher sensitivity (+2) would indicate increased year-to-year changes in sedimentation.

Results

Sediment cores studied

Six sediment cores were selected from the suite of cores available from Lake C2. Five of the cores studied were from a transect taken through the chemocline to the north of the main inflow (Figure 1). The transect consisted of five long cores and a shorter core from water depths of 15–25 m. The uppermost core from the transect (core 81) consisted of diffuse and massive sediments and was excluded from analysis. Core 71 from 38 m depth was the sixth core included in the study. Zolitschka (1996) studied a second transect of cores located between the main delta and the lake outlet (B–B' on Figure 1). Although all of the cores in the delta-outlet transect contained less than 200 varves, the

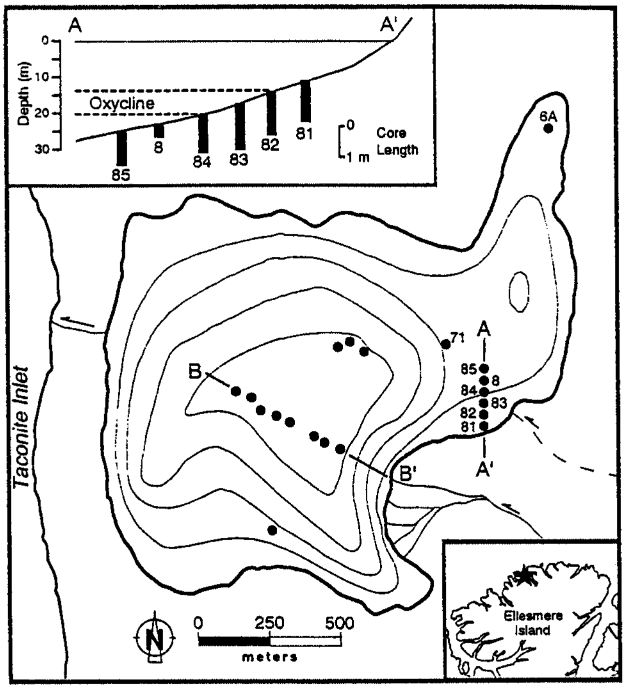

Figure 1. Map of Lake C2 indicating the coring-sites and location of the major inflow stream. Upper inset shows schematic cross- section of transect through the chemocline (A–A'). Cores from transect B–B' were studied by Zolitschka (1996). (Note: 20 m bathymetric contour).

study provides valuable independent verification of the results from this study.

Sedimentation

The cores used in this study represented sediments from upper limit of the oxycline through to the anoxic hypolimnion (Figure 1). The base of each core (with the exception of core 8) was composed of dark grayish brown near-massive mud (Figure 2). Occasionally, faint black lamina, small clasts, and black cysts of unknown composition were observed within the mud. Mollusk shell fragments (unknown species) were recovered from near the base of cores 81, 82 and 84 and were radiocarbon dated (Table 1). The massive mud was interpreted as marine in origin, predating the isolation of the lake from Taconite Inlet, and was similar to marine sediment from the Beaufort Lakes on northeastern Ellesmere Island (Retelle, 1986). The marine unit was overlain by 24–67 cm of finely laminated yellowish brown to dark gray mud. Initially, the mud was black and had a distinctive sulphur odor, but after a short period of exposure, oxidized to reveal the laminae. Core 8 was subsampled from an Ekman dredge and was composed entirely of fine laminae.

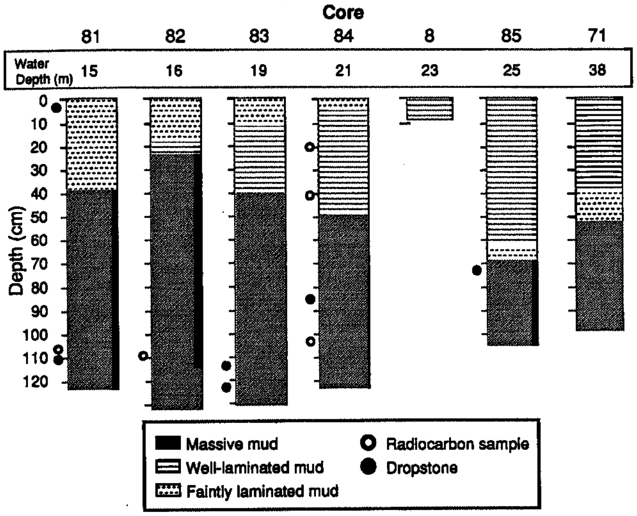

Figure 2. Logs of cores studied.

Several distinctive reddish brown and black laminae were noted in all cores, but the reddish laminae were found only in the lowest few centimeters of the laminae in the long cores.

Thin sections of the laminae revealed several distinctive sedimentary structures. *Microlaminated* sediments were the most frequently observed, consisting of couplets with a light- colored silt and fine sand lower unit and a finer, typically darker upper unit (Figure 3a). Contacts between the clay and silt units were generally sharp, especially between adjacent couplets. *Sublaminated* varves were characterized by sublaminae and other fine structures (Figure 3b) (Zolitschka, 1996). Sublaminated sediments were relatively infrequent in the cores and tended to occur as thicker couplets. *Turbidic* couplets exhibited a distinctive upward fining sequence and gradational contact between the summer and winter units (Figure 3c). Frequently, the base of the turbidites was relatively coarse and occasionally contained plant fragments and other debris. Additionally, the silt/clay layer of the turbidic couplets was commonly dark brown, possibly caused by increased fine organic matter in the clay.

The fourth and least common sedimentary structure observed was composed of mud interpersed with fragments of deformed laminated sediments. The upper and lower contacts were usually sharp, but in one case the basal contact was indistinct and the adjacent couplets were discontinuous (Figure 3d). It is likely that these structures represented gravity-induced slumps with the potential to erode significant amounts of sediment (Dominik *et al.*, 1992). The erosive capability of the slump events was revealed in core 85 where cross-

Table 1. Radiocarbon dates from the cores studied. The dates reported have not been corrected for reservoir effect

Core	Depth (cm)	Material dated	Date	Laboratory sample
C2-81	109	Shell fragments	8420 ± 150	WHOI-3814
C2-82	110	Shell fragments	8440 ± 160	WHOI-3815
C2-84	20	Isolated humin	7700 ± 170	CAMS-11134
C2-84	40	Isolated humin	9070 ± 160	CAMS-11809
C2-84	104	Whole shell	8140 ± 155	WHOI-3816

Note: Samples with WHOI prefix were determined at Woods Hole Oceanographic Institute. Samples with CAMS prefix were determined at the Lawrence Livermore National Laboratory from targets prepared at the University of Colorado.

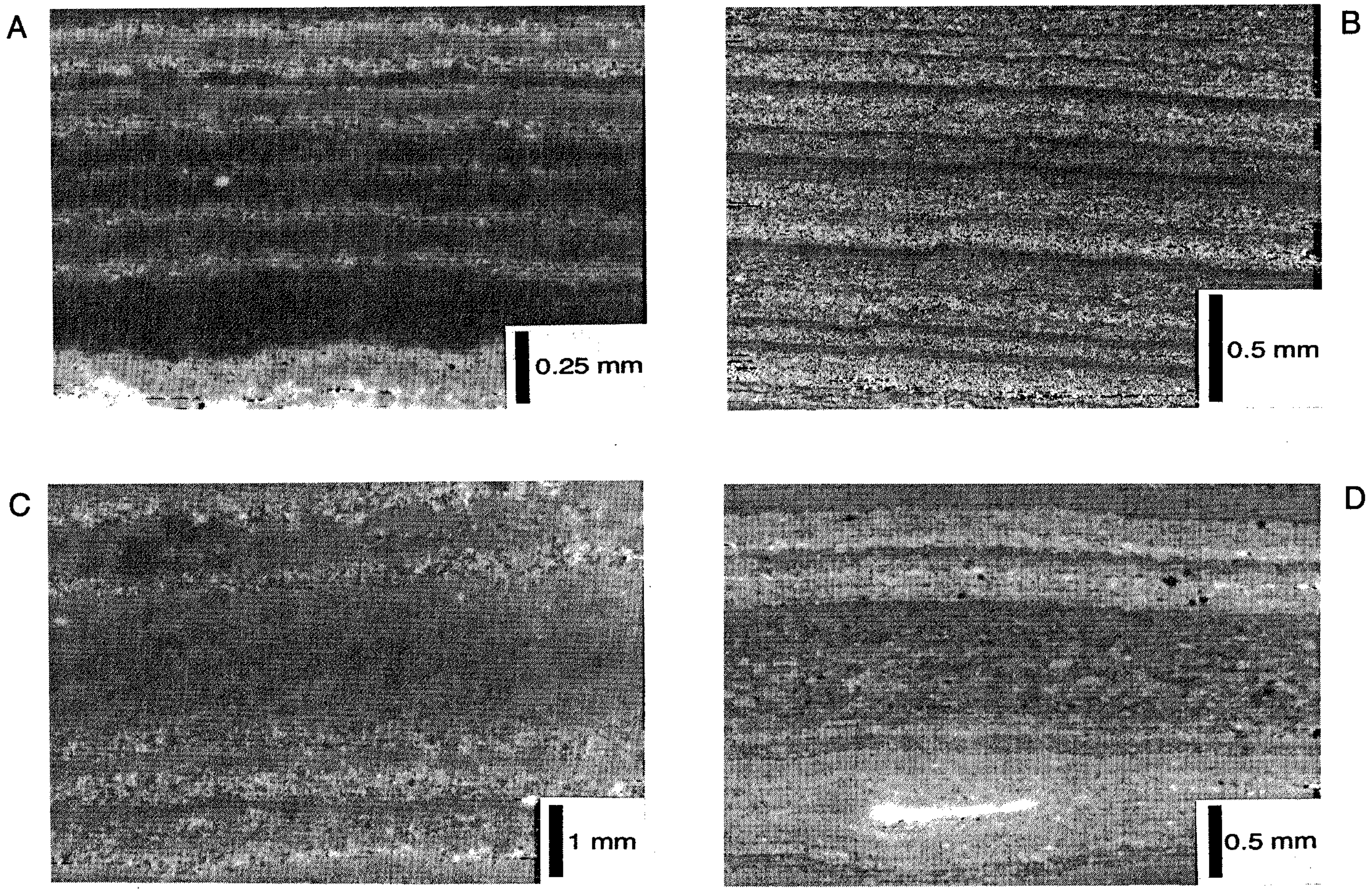

Figure 3. Microphotographs of typical Lake C2 sediment structures: (A) microlaminated, (B) sublaminated, (C) turbidite, and (D) slump deposit.

dating showed that a single slump event had eroded fifty-six varves.

Minor disturbances including microfaulting, undulations and core-edge warping frequently obscured very fine couplets and caused counting errors. Serious disturbances produced by folding, faulting, smearing and erosion were less common, but were observed in all cores studied. In several cases, major disturbances resulted in a large gap of several hundred couplets in the varve measurement series. However, in all cases the break in the series was overlapped by another core, thereby preserving the integrity of the varve chronology.

Sedimentological parameters measured were relatively constant in the laminated units of each core. The mud was composed of near equal proportions of silt and clay, sand was rare (<5%) in all but occasional coarse graded bed, and the bulk density exhibited minimal variation. Because of the relatively uniform grain size and density in the varved sediments in all cores, we believe that changes in varve thickness are the product of changing sediment flux into the lake.

Verification of varve interpretation

Independent verification of the annual interpretation assigned to the laminae is crucial for developing a reliable chronology (Lemmen *et al.*, 1988; Cromack, 1991; Stihler *et al.*, 1992). In addition to the sedimentological evidence for the presence of annual couplets, ^{210}Pb determinations on six samples from a short core in main basin of Lake C2 closely matched the varve counts from the same level and confirmed that the sediments were varved for the last 125 years (Figure 4).

Sampling for radiocarbon dating was hindered by a lack of macro organic material in all of the cores. Bulk sediment samples were submitted for humin extraction to provide independent confirmation of the varves, however, the radiocarbon results contained dating reversals and failed to confirm the varve chronology (Table 1). Furthermore, the ^{14}C dates on humins extracted from the sediments are incompatible with the glacio-isostatic history of the region (Bradley *et al.*, 1996). Similar problems with bulk radiocarbon dates have also been documented elsewhere in the arctic (Abbott, 1991). The shell dates from the base of cores 81, 82 and 84 corroborate each other, however, because of their stratigraphic position, they do not provide confirmation of the varve interpretation. Despite a lack of radiocarbon support, the ^{210}Pb results and the consistency of the sediment structures throughout the cores suggest that the entire sequence is varved, although we lack independent confirmation of the chronology beyond the range of ^{210}Pb dating.

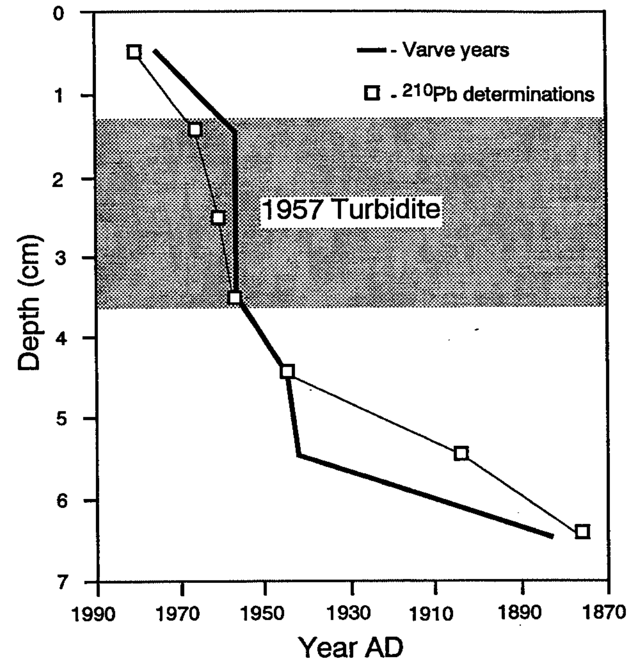

Figure 4. Down core comparison between varve dates and modelled ^{210}Pb dates. Three ^{210}Pb samples were taken from the thick 1957 turbidite, as indicated in the shaded zone (Data from Zolitschka, 1996).

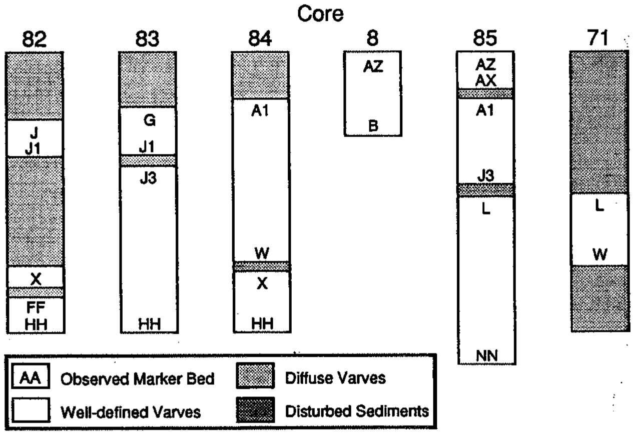

Figure 5. Schematic marker bed stratigraphy for Lake C2. Intervening visible marker beds have been omitted.

Stratigraphy

The accurate lake-wide stratigraphy established with the marker beds identified varying degrees of surface erosion and internal disturbance of the varves (Figure 5). Cross-dating the long cores with short surface cores taken with the Ekman dredge revealed that surface erosion caused by percussion coring in core 85 was limited to fewer than fifty varves. Down-core disturbances observed in some thin sections were overlapped and bridged by one or more of the other cores. In this manner, a continuous record of varve sedimentation was available from the base of the laminae to the surface.

The multi-core stratigraphy also identified the absence of continuously well-defined varve couplets from the upper sections of cores 82–84 (Figure 5). Short sections alterned between well- defined and diffuse laminae that were nearly impossible to differentiate and closely resembled those from above the oxycline throughout cores 6A and 81. Diffuse varves were the dominant feature in all but the lower portion of core 82. By comparison, the deeper cores 83 and 84 exhibited fewer sections of diffuse varves only near the core surface, while cores 8 and 85 from below the oxycline did not exhibit any diffuse varves. We argue that the diffuse varves were formed under aerobic conditions, which allowed bioturbation of the fine sediment structures. The alternation between aerobic and anoxic sedimentation in the proximity of the oxycline suggest that the oxycline depth may have varied in the past (see Discussion).

It is interesting to note that in all of the cores studied, the zone of varves directly above the transition from marine sediment in the core contained abundant couplets with reddish clay layers. Geochemical analyses were not undertaken to further define the nature of the reddish clay, but we suspect that the presence of the reddish clay may indicate the contribution of sediments from areas outside the Lake C2 watershed prior to the isolation of the lake by uplift (see Discussion).

Error analysis of varve counting

Errors were identified in each core by cross-dating between cores and were noted as either missing (Type A) or erroneously identified (Type B) varves. Errors that remain unknown after cross-dating the varve sequences (Type C) are discussed below. Core 82 contained only short varve sequences and is excluded from the analysis.

Cross-dating revealed that the level of error caused by misinterpretation and disturbance in the cores was relatively low. Erroneously identified (Type B) varves were observed in less than 1% of all varves measured in all cores but 71 (Table 2). These results are not entirely unexpected, as the identification of a varve required the observer to actually see evidence for a couplet structure (Sprowl, 1993). The majority of the extra varves occurred in disturbed core sections or were associated with sublaminated couplets.

Missed varves (Type A) were common in all cores, but comprised less than 6% of all varves measured in all cores except 84 (Table 2). The missed varves were thin (<0.07 mm), and were easily obliterated by minor sediment disturbances. Cross-dating revealed that high levels of Type A error were associated with disturbance in specific core sections which were clustered together, suggesting that the core disturbance was isolated and relatively limited in extent. Missed varves were more common throughout core 84, in part due to obscured core sections.

Correlation

Cross-dating revealed that individual varves were consistently observed throughout the cores, were visually well-correlated, and similar statistically (Table 3). Maximum measurements from each core ranged from 0.95 to 6.10 mm, due to the variable influence of the thick turbidites. An ANOVA test between the cores revealed that there was no significant difference (at 99%) between measurements in all but core 71, permitting direct comparison between paired measurements from all of the cores except 71.

Core 8 contained the uppermost varves and was highly correlated with measurements from two deep water (proximal) cores ($r = 0.80$–0.97) for the past 150 years. The high degree of correlation between core 8 and the cross-dated chronology from deeper water (which was confirmed by the ^{210}Pb analysis; Zolitschka, 1996) confirms that the varves are well distributed throughout the lake and that a varve measurement chronology from the shallower cores is representative of lake-wide sedimentation. Correlation between the cores in this study and initial measurements of a long core from 84 m depth appears poor. At this time, it is difficult to reconcile the differences between the two chronologies, as both records correlate well for the first 150 years. Moreover, the good correlation between the records ends at a break between cores in the deep chronology and no additional cores are available to reproduce the deep chronology. Therefore, although we recognise that an alternate chronology exists, we feel that the series reported here is reproducible and accurate. New deep cores and further analysis are required to resolve this issue.

Correlation between raw data from the distal cores in this study was also uniformly high, ranging from $r = 0.83$ to 0.96, and significant at 99%. The statistical correlation between the cores confirmed the visual correlation observed during the cross- dating phase. Correlation coefficients determined for individual counting sections were high, the exceptions involving isolated thick graded couplets that were up to four times thicker than the corresponding couplets in the other cores. The very high correlation between the remaining core sections suggested that the majority of the paired-varves, including the thicker graded beds, were similar in magnitude as indicated by the ANOVA.

Table 2. Weighted whole-core errors for the core segments studied

Core	C2-83	C2-84	C2-8	C2-85	C2-71
Number of varves	453	1991	323	2628	143
% Extra (Type A)	0.66	0.90	0.31	0.41	1.38
% Missed (Type B)	1.10	11.50	4.33	6.33	3.45
% Net (Type A+B)	0.44	10.60	4.02	5.92	2.07

Table 3. Statistics for each sediment core studied

Core	C2-83	C2-84	C2-8	C2-85	C2-71
Number of varves	453	1991	323	2628	145
Mean thickness (mm)	0.11	0.17	0.20	0.18	0.20
Standard deviation (mm)	0.09	0.23	0.20	0.20	0.19
Minimum thickness (mm)	0.03	0.03	0.04	0.04	0.04
Median thickness (mm)	0.09	0.12	0.15	0.12	0.13
Maximum thickness (mm)	0.95	6.10	2.72	3.90	1.22

Composite chronology construction

The high correlation and statistical similarity between the measurements from different cores permitted the construction of a composite thickness series to provide a continuous varve record. Two composite series were constructed, one based on raw data and another on data filtered to remove measurements suspected as graded.

In order to compare the cores with each other, the measurement series had to first be standardized. Each data series was tested for normality using the Kolmogorov-Smirnov one sample test. Results of the tests revealed that none of the series were normally distributed, necessitating a non-parametric method for standardizing the data. An alternative method for standardizing the data was a simple dendroclimatological index defined as:

$$x_i = \frac{x_o}{x_e}$$

where x_i is the index value, x_o is the observed value and x_e was the expected value from a tree growth function (Fritts, 1976). For the varved sediments, the tree growth function was replaced by a linear least squares function derived from the varve measurement series. It is interesting to note that the linear trends from cores 84 and 85 were nearly the opposite of each other, suggesting that different influences may have caused the trends. Because the trends had opposite signs, it is unlikely that the trends were produced by climatic or geomorphic processes. One possible explanation is that the trends were caused by compression or extension of the sediments during coring or subsequent transport. For construction of the varve thickness indices, expected values were calculated from the linear trends, effectively standardizing and detrending the raw varve data simultaneously.

Two composite indices composed of unfiltered and 'filtered' data were constructed by averaging the index values from cores 8, 83, 84 and 85. In the filtered data series, couplets identified as turbidites were replaced with the series mean. Measurements from up to three cores contributed to each value in the final 3300 year composite indices with the majority derived from two cores. Potential bias caused by using different numbers of contributing cores was investigated by constructing histograms of the index values constructed from a given number of cores. Index values averaged from 1–3 cores exhibited a similar unimodal distribution with no major variations, suggesting that no significant bias was introduced to the composite series.

Disruptions in all but one core prevented cross-dating for three sections of the composite: 3300–3106, 1542–1300, and 255–158 BP (varve years before 1991). Caution must be used when interpreting the sections of the composite record that were derived from data that was not cross-dated. Although no visible relationships or inconsistencies occur during periods without cross-dating, net errors of 0.4–10.6% (Table 2) or more could exist.

Several periods of above and below mean sedimentation occurred during the length of the record (Figure 6). High-amplitude (or peak) events were relatively common during the same periods. The high sedimentation rate during 3300–3100 BP abruptly ended compared with later periods of above average sedimentation. High sedimentation gradually decreased from ca. 1200–900 and 400– 250 BP. The periods of 3000–2300, 900–750, and 250–100 BP were characterized by below average rates of sedimentation accumulation and infrequent peak events. The amplitude of the extreme events during these periods was considerably lower than those observed during times of higher sedimentation.

It is interesting to note that the last century has exhibited higher sedimentation rates (Figure 6). It could be argued that a single major turbidite at 34 BP (1957 AD) influenced the record, providing a false signal. However, when the turbidite was removed by filtering, it was revealed that several peak events bracketed the major turbidite, and increased the century-scale sedimentation level.

Measurement of the inter-annual variability with the mean sensitivity statistic (ms_x) reveals additional complexities in the observed changes to the sedimentation rate. Sensitivity in both series was above the mean during 2300–700 and 200–0 BP and was closely related to increased sedimentation and frequent peak events (Figure 6). The exception to the case was a brief interval of lower sedimentation from 900–700 BP which exhibited variable, but generally higher sensitivity.

Periods of low mean sensitivity (3100–2300 and 700–200 BP) did not occur uniformly between the unfiltered and filtered series (Figure 6). Overall, the unfiltered series showed higher sensitivity but differed in trend from the filtered series during two periods. For example, from 700–500 BP the sensitivity of the unfiltered series decreased to average levels while the sensitivity of the filtered composite remained low. During 3100– 2300 BP the difference between the sensitivity of the unfiltered and filtered series decreased and between 3100–2600 BP the two series showed near-identical levels of sensitivity. Moreover, the convergence of filtered and unfiltered sensitivity occurred during the lowest period of sensitivity measured and during an extended period of below average sedimentation. Both lines of evidence suggest that the influence and frequency of peak events on the rate and variability of sedimentation during this period was comparatively low and was distinct from other periods of low sensitivity where sedimentation was relatively high (e.g. 500– 400 BP).

Estimated chronological error of composite chronology

The potential error in the composite chronology introduced by varve sections that were not cross-dated can be estimated from the errors observed during cross-dating (Table 2). As most of the sections of the composite series that were not cross-dated were obtained from core 85, the error estimates are based on weighted observed errors from that core. Additionally, because Type A (missed) and Type B (extra) errors would be expected to cancel each other out, the difference between the weighted errors was a reasonable net error estimate for the 957 years (29%) of the chronology that were not cross-dated. On this basis, the estimated error caused by core sections that were not cross-dated was ±57 years, or 1.7% of the entire composite.

The final estimate of the error in the prepared varve chronology is tentative for several reasons. Cross-dating permitted identification of the errors contained in individual cores, however, the error common to all of the cores studied remains unknown (Type C error). The high degree of correlation between the distal transect sediments in this study and the first 150 years of data from proximal sediments (Zolitschka, 1996) suggest that sediment was consistently distributed throughout the lake, reducing the possibility of all three types of error. Moreover, cross-dating of the independently-produced proximal and distal chronologies revealed only two missing or extra varves. Therefore, two known errors (Type C) exist between the distal and proximal varve chronologies for the past 150 years. Although only approximately 7% of the 3300 year distal chronology could be compared with the independent data from the proximal sediments, the results suggest that the all three types of error must at least be low.

Discussion

Changes in varve sedimentation

In cores from well below the oxycline (>25 m) varved sediments are clearly visible, while in cores from shallower depths (in the oxygenated mixolimnion), varves are poorly discerned. We hypothesize that varves are best preserved under anoxic conditions, and any changes in the occurrence of varves in a core reflects a change in oxygenation of the overlying water column.

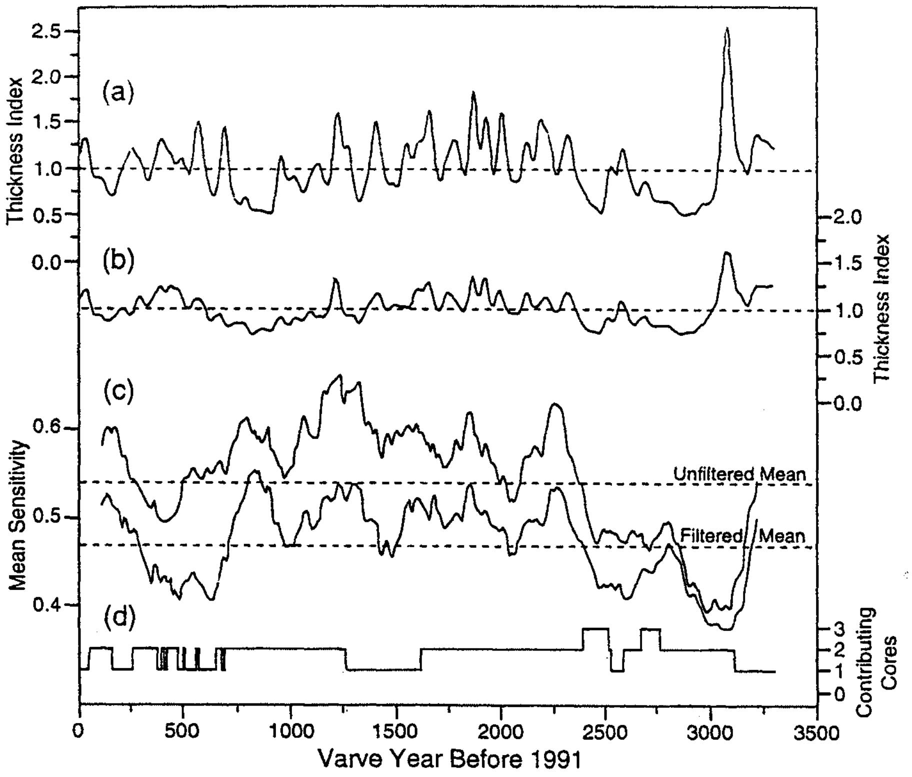

Figure 6. Composite varve sedimentation series from Lake C2. (a) Unfiltered series and (b) filtered series (i.e. without extreme events) have been treated with a 100 year Gaussian smoothing. Mean sensitivity (c) is measured with a 200-year moving average. The number of cores contributing to each composite series measurement is indicated (d).

Oxygenation would permit bioturbation of the thin sedimentary structures, obscuring the original layering.

In the transect of cores from 15–25 m water depth, there is a progressive change from well-defined varves at depth, to diffuse varves in the uppermost sediments (Figure 7). The transition between well-defined and diffuse varves is characterized by alternating thin units of well-defined varves separated by diffuse sediments. Through the transition zone, the sections of well-defined varves become progressively less frequent, finally yielding to uniformly diffuse sediment. By cross-dating the varves, it is apparent that the shift from well-defined to diffuse varves occurs at a later date with increasing depth in the transect (Figure 7). Evidently the threshold depth at which varves were preserved oscillated around 16 m prior to ~1250 BP. Deepening of the oxygenated zone (by ~5 m) then occurred over a relatively short period of time. The observed depression could have resulted from increased oxygen flux to the lake due to increased freshwater inflow, however, there is no support for progressively higher sedimentation (and hence streamflow) in Lake C2 over the past 1250 years. Moreover, the higher sedimentation from ~2600–1200 BP did not result in a permanent decline in the aerobic zone (Lamoureux, 1994b). Alternatively, a deeper oxygenated zone may have resulted from lower snowfall and/or thinner ice cover, allowing greater penetration of solar radiation in the spring and summer months and higher levels of photosynthetic activity (i.e. a deeper compensation depth). Field measurements reveal that the base of the oxycline is related to the depth that photosynthetically-active-radiation (PAR) penetrates into the water column (Ludlam, 1996a). Short-term changes in lake ice and snow cover thickness or the extent of the summer moat development can dramatically change the depth of PAR penetration. Hence, the observed pattern of diffuse and well-defined varves may be related to a systematic change in snowcover or ice thickness after ±1250 BP, leading to modern conditions in which aerobic conditions in the near-surface waters preclude varve formation above ~22–23 m water depth.

An alternative explanation for the decline in the base of the aerobic zone in Lake C2 is that the lake outlet stream may have rapidly incised into the sill separating the lake from Taconite Inlet after 1250 BP, causing a corresponding lake-level lowering. Assuming that the epilimnion thickness was relatively constant dur-

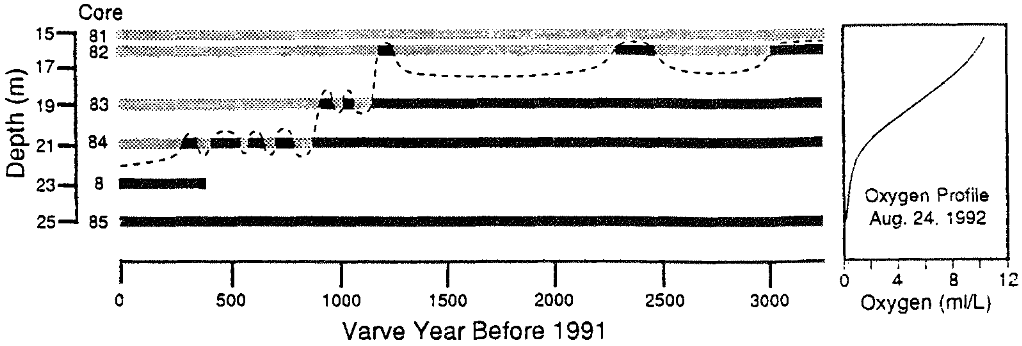

Figure 7. Schematic representation of diffuse and well-defined varves in transect through oxycline. Diffuse varves are indicated by hatched areas. A typical late-summer oxygen profile indicates the core depths through the oxycline.

ing the same period, a lake-level lowering would cause mixing and dilution of the hypolimnion, increasing the oxygenated depth relative to the coring sites. The outlet gradient between the lake and inlet would have been initially low, preventing significant incision; with continued uplift, the outlet stream would steepen and erode into the sill. However, such a process is likely to have been gradual and can not account for the apparent fluctuations in depth of the oxygenated zone shown in Figure 7; we thus favor a climatic interpretation for the observed changes.

Environmental significance of sedimentation in Lake C2

Process studies at Taconite Inlet have revealed the complex inter- relationships between climate and sediment flux (Hardy, this volume; Hardy *et al.*, 1996). The factors controlling sedimentation and the thickness of a varve are not simple, involving the interaction of both climatic and geomorphic controls, as well as within-lake processes, which may vary in importance over time. For example, we can not be certain that low-frequency trends in varve thickness are entirely climatically controlled since geomorphic controls on sedimentation (such as a shift in the main delta distributary) may be reflected in the varved record (Leonard, 1985; Desloges, 1994). However, as discharge and suspended sediment flux are strongly related to summer air temperature (Hardy *et al.*, 1996) it is reasonable to interpret the long-term varve thickness record as a proxy of summer temperature until other factors can be demonstrated as having been of more importance. Similarities between the varve thickness record and other temperature proxies (discussed below) support this conclusion.

Lake Holocene paleoenvironment (4000–1000 BP)

Strong evidence exists for a gradual late-Holocene climatic cooling. In the Agassiz, Devon Island and Camp Century ice cores, $\delta^{18}O$ values declined by approximately 3‰ and melt layers became less frequent from ca. 5000 BP (Paterson *et al.*, 1977; Koerner & Fisher, 1990). Koerner & Paterson (1974) propose that the Meighen Ice Cap formed during 4500–3000 BP, with cooler and positive mass balance conditions indicated by increased bubbles in the ice. However, the dating of this interval in the Meighen core is speculative and based on the assumption that the ice cap could not have survived the warmer mid-Holocene climate (Bradley, 1990).

Late Holocene cooling is also shown by the advance of several glaciers that incorporated mid-Holocene biota into their deposits (Bradley, 1990). Following ~3800 BP, driftwood became relatively rare on the coast of northern Ellesmere Island, suggesting increased severity of sea ice conditions, concurrent with the development of the modern ice shelves (Stewart & England, 1983). Initial development of the Ward Hunt Ice Shelf is estimated to have occurred after ~3400 BP, based on dated organic and shell remains frozen to the base of the shelf and subsequently ablated at the surface (Lyons & Mielke, 1973; Jeffries & Krouse, 1984). Similarity, driftwood was apparently absent from Clements Markham Inlet to the east of the Ward Hunt Ice Shelf from 4200–2200 BP and from Yelverton Inlet to the southwest after 4310 BP (Evans, 1988). It is likely that ice shelves developed in many locations along the north coast of Ellesmere Island during this period, however, the absence of a modern ice shelf at Clements Markham Inlet points to the ephemeral nature of the features (Stewart & England, 1983; Bradley, 1990; Jeffries, 1992).

From ~3300–3000 BP the varve sedimentation rate was relatively high and the mean sensitivity decreased significantly from 3200–3100 BP (Figure 8). The Devon and Agassiz ice core records for the same period do not exhibit major $\delta^{18}O$ reductions, although the Camp Century $\delta^{18}O$ record is relatively low during the same period. Comparison between the varve and ice core records reveal no consistent climatic signal for this period. At 3000 BP, relative sea level in the region was at 10–12 m asl (Bednarski, 1986) therefore, the modern lake basins would not have been completely separated from Taconite Inlet. However, the presence of varves in the Lake C2 basin at 3300 BP suggests that Taconite Inlet was isolated from the main ocean circulation by that time, resulting in density-stratified conditions in the inlet and similar to current conditions in the inlet and Disraeli Fiord (Lemmen, 1990; Ludlam, 1996b).

The period from 3000–2400 BP consisted of low $\delta^{18}O$ values in the high arctic ice cores and low varve sedimentation at Lake C2 (Figure 8). Additionally, the same period of the varve record was characterized by low mean sensitivity for both filtered and unfiltered data. The combination of low sedimentation and small inter-annual variation suggests uniformly colder conditions with reduced sediment transfer due to decreased snow cover, or by reduced nival peaks. Lower $\delta^{18}O$ values recorded in the ice cores suggest that colder conditions, reduced precipitation, or both may have been frequent during 3000–2500 BP.

It is interesting to note that the red-colored clay units in the Lake C2 varves that were common from 3300 BP abruptly ended at approximately 2665 BP. Without geochemical analyses, the significance of the red varves can only be speculated. However, it is possible that the red varves were deposited prior to the isolation of the Lake C2 basin from density-stratified Taconite Inlet. A distinctive red-colored conglomerate member of the Taconite River Formation is commonly exposed in the Taconite River valley, but infrequently in the Lake C2 watershed (Trettin, 1989). It is possible that the clay in the red varves originated from this formation and was transported via the Taconite River. The Lake C2 basin is distant from the outlet of the Taconite River, and would only receive suspended clay sediments. Because the deposition of the red clay from the Taconite River would cease following the isolation of Lake C2, the last red varve may accurately date the isolation. Assuming the lake threshold was limited by the 10 m sill separating Lake C2 from Taconite Inlet, the estimated date of isolation would be consistent with the regional uplift curve (Bednarski, 1986).

From ~2500–1200 BP, varve sedimentation and mean sensitivity were both consistently above average and highly variable (Figure 8). Removing extreme events reduced both the sedimentation rate and the mean sensitivity, but both measures still exhibit a high degree of variability. Similarly, the residuals from the ice cores are also above the mean during that period. Several prominent peaks in the ice core isotopic records correspond to periods of higher $\delta^{18}O$ several hundred years in length but do not coincide with similar peaks in sedimentation. Century- scale mean sensitivity peaks occur during the same period and appear in the unfiltered and filtered data. Turbidite events were frequent, possibly due to higher sediment flux and the oversteepening and slumping of the Lake C2 delta face. The concurrent $\delta^{18}O$ increase in the high arctic ice cores supports the interpretation of relatively warm and variable conditions. Although a change in source area or seasonality of the precipitation can not be ruled out, the isotopically heavy precipitation resulting from either scenario would be consistent with an increased southern synoptic influence in the high arctic. Similarity, it is thought that the Meighen Ice Cap underwent a period of near-continuous negative mass balance from 2500–2000 to 660 BP, as indicated by ice that is relatively clear and free of bubbles caused by frequent melting conditions (Koerner & Paterson, 1974). Although there are no reliable dates on the Meighen ice core, the climatic interpretation of the Lake C2 varves supports the interpretation of warmer conditions during this period.

Pollen deposition in the Agassiz Ice Cap during 2500–1000 BP was generally high and variable. Pollen concentrations peaked from 1600–1000 BP and were dominated by exotic species (Bourgeois, 1986). The pollen evidence supports the interpretation of increased penetration of southern synoptic systems into the high arctic. Moreover, the peak pollen concentrations at 1600–1000 BP coincide with the highest mean sensitivity in the Lake C2 varves. Finally, it is of interest that the Dorset culture expanded during the period of 2500–1200 BP, possibly related to the warmer conditions at that time (Sutherland, 1992). Additionally, radiocarbon dates associated with Independence II sites from northern Ellesmere Island and northwest Greenland are clustered between 2500–2300 BP.

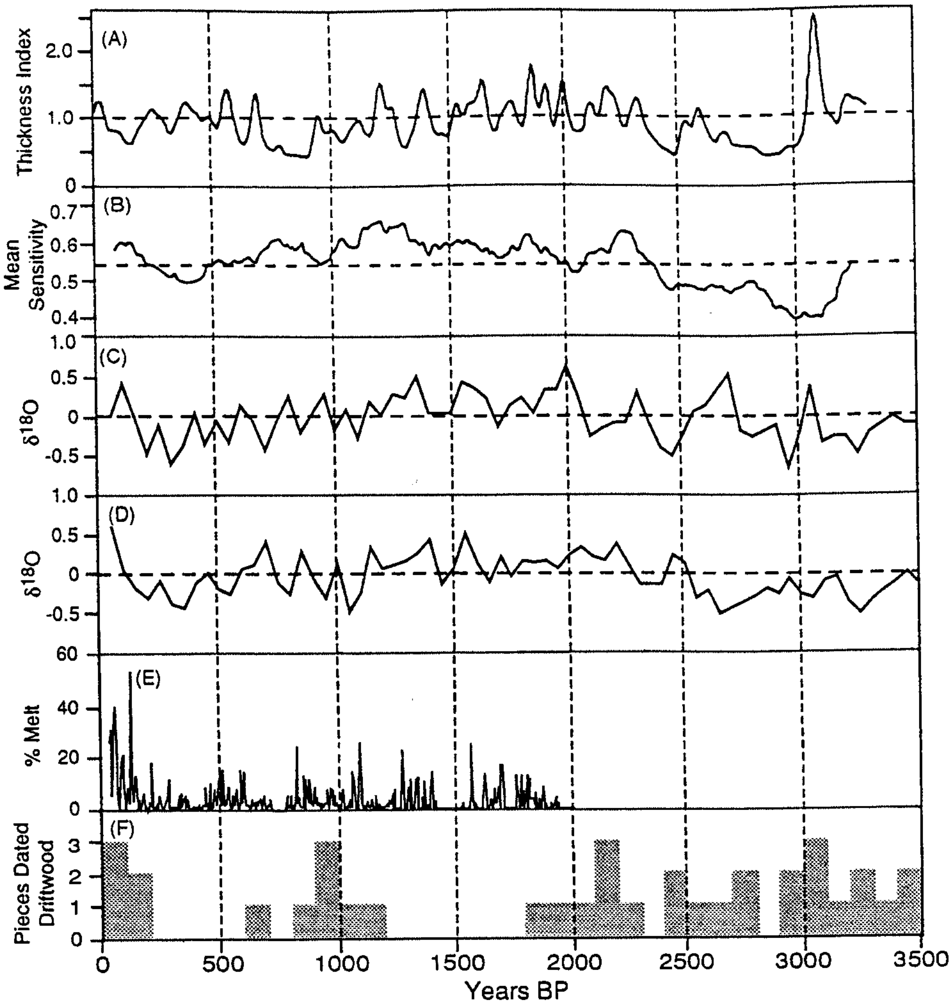

Figure 8. Reconstructed proxy records of late-Holocene High Arctic climate. Panels show (A) unfiltered varve sedimentation, (B) sensitivity, (C) detrended ice cores $\delta^{18}O$ for the Camp Century and (D) Devon ice cores, (E) melt layer frequency from the Agassiz Ice Cap, and (F) dated driftwood from the High Arctic for the past 3500 years. Agassiz data provided by D. Fisher, driftwood data from Bradley (1990), and Devon and Camp Century isotope records from Paterson *et al.* (1977).

Recent environmental changes (1000–0 BP)

The varve thickness at Lake C2 gradually declined from ca. 1500 BP into a period of relatively stable low sedimentation at 900– 700 BP (Figure 8). During this period the mean sensitivity of the varves was relatively high, however, the difference in sensitivity observed between the unfiltered and filtered varve series decreased. This suggests that the sensitivity during this period was produced by increased inter-annual variability in the data as a whole, and not exclusively by high amplitude turbidites. Because the sensitivity of this period was similar to the previous 1800 years, the lower sedimentation rate suggests different climatic conditions occurred.

Ice core $\delta^{18}O$ records for 900–700 BP are highly variable. Isotopic values in the Agassiz, Devon, and Camp Century cores show some decline from ca. 1500 BP but remain relatively high during 1000–500 BP (Figure 8) (Paterson *et al.*, 1977). Additionally, melting on the Agassiz and Devon Ice Caps increased from 900–800 BP and the Meighen Ice Cap was likely undergoing ablation during the same period (Koerner & Paterson, 1974). At the same time, both regional and exotic pollen concentrations were generally low in the Agassiz ice core (Bourgeois, 1986). Although the varve sedimentation rate, ice shelf thickening, and pollen record from Agassiz Ice Core suggest cooler conditions, the ice core isotopic evidence suggests variable but generally warmer climate.

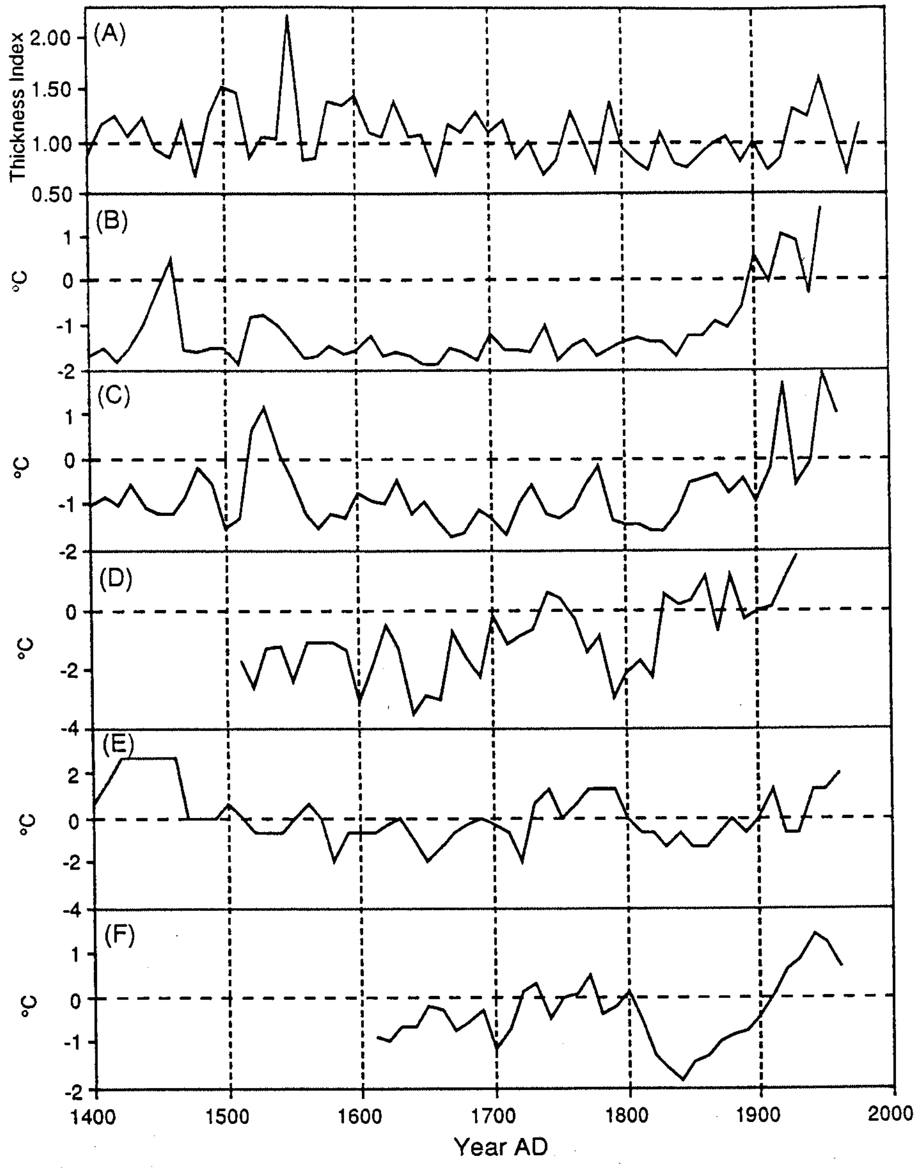

Figure 9. North American 'Little Ice Age' proxy records. Panels show (A) unfiltered varve sedimentation from Lake C2; summer temperature inferred from (B) Agassiz Ice Cap, (C) Devon Island Ice Cap, and (D) south Greenland melt records; (E) pollen from Lake of the Clouds, Minnesota; and (F)tree-ring thickness variations at the treeline in northern North America. Non-varve data are in °C units and are standardized to the reference period of 1860–1959 (data from Bradley & Jones, 1993).

Sedimentation during 700–250 BP increased at Lake C2 and was characterized by several prominent peaks defined by thick turbidites. Mean sensitivity decreased from a high at 750 BP to a low at 350 BP but the unfiltered and filtered data reacted differently (Figure 8). The decline in sensitivity of the unfiltered series was delayed until ca. 500 BP, followed by a sharp decrease at 400–300 BP. Sensitivity of the filtered series decreased rapidly from 700–600 BP and remained relatively low until 300 BP. The divergence in sensitivity shown by the unfiltered and filtered series (the largest measured in this study) suggests that the sedimentation in Lake C2 differed in nature before and after ca. 450 BP (Figure 8).

Melt layers in the Agassiz and Devon cores are frequent from 700– 450 BP, and decrease thereafter until 200 BP. Additionally, only one driftwood sample from the arctic islands dates between 700– 300 BP (Stewart & England, 1983). In contrast, pollen concentrations in the Agassiz core increased marginally from 500–200 BP (Bourgeois, 1986).

Increased sedimentation, frequent melt layers, and increased pollen flux suggest that during 700–300 BP conditions were warmer, possibly with higher precipitation. The period was also characterized as relatively sensitive prior to 450 BP, and insensitive thereafter. However, it is possible that the amelioration during this period was limited: δ^{18}O isotope values in the ice cores were declining and sea ice appears to have been persistent. Moreover, the importance of episodic sedimentation from 700–450 BP is evidenced by the higher sensitivity of the unfiltered series. The decrease in varve sensitivity following 450 BP may be related to the gradual decline in temperature suggested by isotope and melt layer data from the high arctic ice cores, and more pervasive sea ice.

Relatively low sedimentation during 250–100 BP was followed by an increase to the present. A similar increasing trend occurred in both filtered and unfiltered sensitivity from 300 BP and was enhanced slightly from 200–100 BP in the unfiltered series, indicating the increased importance of sedimentation by turbidites (Figure 8). Data from the ice cores showed increasing δ^{18}O and frequent melt layers from ca. 200 BP. Additionally, driftwood became abundant throughout the arctic islands after 250 BP (Stewart & England, 1983). Finally, there is evidence from the high arctic that diatom assemblages changed significantly during the past 100 years (Doubleday *et al.*, 1994; Douglas *et al.* 1994).

The independent evidence supports the interpretation of a climatic warming following 200 BP at Lake C2 and throughout the high arctic. High arctic proxy records of the past 500 years appear to record elements of the 'Little Ice Age' (LIA). Although the LIA has been applied to various colder periods during the past 600 years, a recent survey of available proxy climate records has revealed that the LIA was not a synchronous global event with regional variations in the timing and strength of colder periods (Bradley & Jones, 1993). Nevertheless, the varved sedimentation signal from Lake C2 shares several key elements of the climatic fluctuations that define the LIA in North America and the Northern Hemisphere. The coldest conditions of the last 600 years appear to have been during the 17th and 19th centuries. Warmer conditions have generally occurred during ca. 1400–1550, 1750–1800, and after 1920 AD (Bradley & Jones, 1993). These general patterns are evident in several North American proxy records, including ice cores from the high arctic and Greenland, fluctuations of tree-ring width at the northern treeline, and in the pollen from varved lake sediments in Minnesota (Figure 9). The sedimentation record from Lake C2 resembles these records, particularly from the 18th–20th centuries indicating that the sedimentary record at Lake C2 has responded to large-scale climatic variations during the past 600years.

Conclusion

This study has developed the first high-resolution record of sedimentation from the Canadian high arctic. An annually-resolved varve record has been prepared from multiple sediment cores and has been cross-dated to minimize counting and interpretation errors. Analysis of the Lake C2 composite series has revealed a complicated sedimentation signal that has varied considerably during the late Holocene. Periods of higher sedimentation were generally associated with increased mean sensitivity and more frequent peak events. Conversely, lower sedimentation rates were generally related to lower sensitivity and infrequent peak events.

Process studies have developed a quantitative relationship between varve sedimentation and air temperatures above the surface inversion layer (Hardy *et al.*, 1996). On the basis of this interpretation, the sedimentation record shows a high degree of correspondence with ice cores and other arctic proxy climate records. The similarities between the constructed varve chronology and other paleoclimatic proxies provides support for our climatic interpretation of the varved sediments. The correspondence between the Lake C2 record and other North American proxy records from the past 600 years reveal that several climatic fluctuations appear to have occurred over a very wide area.

Because of the high accuracy of the varve chronology, the Lake C2 record provides an ideal chronological framework for the timing of late-Holocene high arctic paleoenvironmental events. The paucity of detailed paleoenvironmental data has seriously limited a full understanding of late-Holocene climatic variations. In particular, poorly-dated events such as the growth and decay of ice shelves on the north coast of Ellesmere Island can be better understood by reference to the Lake C2 record. Similarly, the varve chronology provides an accurate framework for investigations of other environmental measures, including microfossil and geochemical proxies in the sediments.

Finally, this research has demonstrated that varved sediments can provide useful paleoclimatic information. It is likely that other high arctic meromictic lakes can provide similar detailed records of past environmental conditions. Future research should be directed at identifying other suitable lakes in the arctic to increase our understanding of natural climate variability in high latitudes.

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