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The Taconite Inlet Lakes Project: a systems approach to paleoclimatic reconstruction *

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Abstract

A comprehensive study of meteorological, hydrological, limnological and sedimentological conditions in the watersheds of density-stratified (meromictic) lakes around Taconite Inlet, northern Ellesmere Island, N.W.T., Canada was carried out from 1990–1992. Lakes C1 and C2 contain seawater 'trapped' by isostatic uplift as the former embayments became isolated from the sea. These lakes, and Lake C3, contain varved sediments which provide an annually resolvable paleoclimatic record. By studying the major systems influencing sedimentation in one of these lakes (Lake C2) a better understanding of the climatic controls on varve formation, and hence on the paleoclimatic signal in the varved sediment record, was obtained. The varves of Lake C2 provide a proxy record of summer temperature for the region.

Introduction

Twenty five years ago, a group from the Canadian Defense Research Establishment made the remarkable discovery that several coastal lakes on northern Ellesmere Island contain saline water, isolated from the atmosphere beneath a freshwater layer (Hattersley-Smith *et al.*, 1970) (Figure 1). Because of the large density difference between the deep saline water and the overlying freshwater layer, the lakes are strongly meromictic, that is, they do not experience seasonal overturning. Apart from a brief visit to these lakes by M. Jeffries in 1984 (when temperature measurements and water samples were recovered) no further research on the lakes has been carried out since Hattersley-Smith's original observations in the 1960s.

Meromixis in Arctic lakes results from three basic processes:

1. isolation of saline bottom waters in coastal lakes due to recent isostatic uplift (e.g. Lakes 'A' and 'C' on northern Ellesmere Island; Hattersley-Smith *et al.*, 1970; Jeffries *et al.*, 1984);
2. 'ecto-cryo-crenogenic' processes, in which saline porewater is expelled from groundwater, due to aggradation of permafrost following emergence (as suggested for Sophia Lake, Cornwallis Island and Garrow Lake, Little Cornwallis Island; Pagé *et al.*, 1984, 1987; Ouellet *et al.*, 1987; Dickman & Ouellet, 1987);
3. isolation of fiord waters by a glacial advance across the fiord to impound a density-stratified proglacial lake (e.g. Lake Tuborg, Ellesmere Island; Hattersley-Smith & Serson, 1964; Long, 1967).

The density-stratified lakes of Taconite Inlet (Figure 2) result from the first of these processes and are of

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

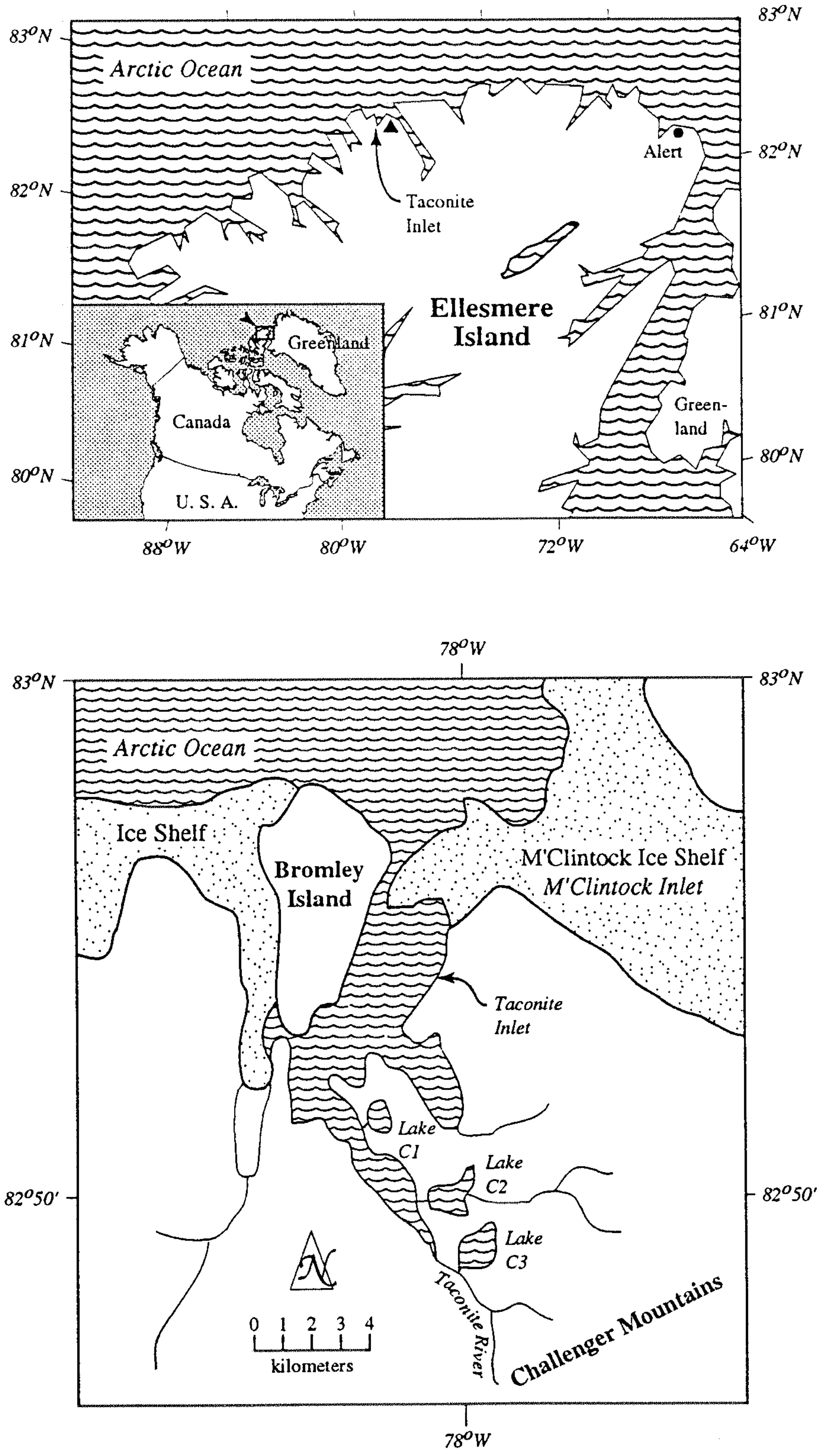

Figure 1. Location map: Taconite Inlet area, with regional location inset.

particular significance for a number of reasons. First, they represent a stage in the evolution of many arctic coastal lakes, when uplift may have caused temporary impounding of marine waters as fiords and coastal inlets became sealed off as lakes. Depending on the elevation of the lake, its bathymetry, and the freshwater throughflow, such lakes may have retained marine waters for hundreds or even thousands of years (as is the case for the northern Ellesmere Island lake. The lakes therefore provide a window on the past, a synoptic view of geochemical, biological and sedimentological processes occurring today, which must have been typical at many locations in earlier times. In particular, during the very rapid uplift which typified many areas in the early Holocene, it is likely that many inlets were rapidly cut-off from the sea, faster than the rate at which the freshening of water in the lacustrine system could keep pace. This would have been especially true of deep embayments receiving relatively little discharge through the lake system. Thus sediments in many lakes, from the period just after lake isolation, may have been deposited in conditions similar to those seen today in the density-stratified lakes of northern Ellesmere Island.

Secondly, the net effect of stratification is to eliminate any direct contact between the bottom waters of the lakes, and the atmosphere, leading to anoxic conditions in the bottom waters (monimolimnion). Anoxic conditions preclude (or at least minimise) the presence of burrowing organisms, which would otherwise disturb the lake-bottom sediments. Consequently, sediments from arctic density-stratified lakes are finely laminated, reflecting the strongly seasonal nature of sediment influx to the lakes. Indeed, it is likely that annually laminated sediments (true varves) can be recovered from many of these meromictic lakes, providing a yearly record of sediment transfer to the lake since uplift caused them to become isolated.

If the varved records can be interpreted or calibrated in climatic terms, it may be possible to construct high resolution paleoclimatic records from many locations. In the Arctic, only ice cores can provide paleoclimatic information with comparable resolution, and there are currently only two locations in the Canadian High Arctic with such records (Devon Island Ice Cap, and Agassiz Ice Cap, Ellesmere Island). Density-stratified lakes offer the prospect of more widely distributed high resolution paleoclimatic records from throughout the Arctic. Furthermore, even in lakes which are not currently meromictic, it may be possible to obtain early Holocene samples of varved sediments from *beneath* sediments which are not laminated, if such lakes experienced a period of meromixis following uplift and isolation from the sea. In theory, a suite of lakes at various elevations along an uplift curve, could provide a set of overlapping varved sediments spanning the entire Holocene or post-glacial period.

Climatic significance of varved sediments

What is the climatic signal in varved sediments from Arctic meromictic lakes? The flux of sediment to Arctic lakes is strongly seasonal, with streamflow (in the Canadian Arctic Islands) restricted to the period mid-May to mid-September (3–4 months; Woo, 1983). Complete ice cover for the other 8–9 months of the year precludes further clastic sediment input, permitting only the gravitational settling of suspended fine material (fine silt and clay from the water column) to contribute to further sedimentation. Biogenic flux is similarly seasonal, though the exact timing of maximum autochthonous biogenic production may well differ from that of clastic material, being controlled mainly by nutrient availability and light conditions (Hobbie, 1984). In a general sense, the thickness and composition of an individual varve should thus reflect climatic conditions during summer months. However, the specific climatic controls (e.g. total solar, or net, radiation, mean or maximum temperature, cumulative degree days etc.) and the role of isolated synoptic events (e.g. heavy rainfall) are unclear. Furthermore, summer runoff (and hence sediment and nutrient flux) will be partly determined by the amount of winter snow accumulation in the watershed. The influence of such external factors is further complicated by within-lake processes, involving sediment re-distribution, by currents and turbidity flows, drifting ice cover etc.

To examine the processes controlling varve sediment formation in an Arctic meromictic lake, the interdisciplinary Taconite Inlet Lakes Project was initiated on northern Ellesmere Island. The papers accompanying this introductory overview provide details of the main elements of the research carried out: meteorological, hydrological, limnological, and sedimentological. Our main objective was to better understand contemporary processes operating in the watershed and hence the climatic signal contained in the sedimentary record (Table 1). Such process-based studies are an essential component of paleoclimatic research, especially in regions where long-term climatic data are sparse or absent. Research focused on:

Figure 2. Oblique air photograph looking eastward across Taconite Inlet towards M'Clintock Inlet (upper center). The meromictic lakes C1, C2 and C3 are indicated. Lakes A and B, first studied by Hattersley-Smith *et al.*, 1970 are also shown. Weather station Alert is on the coast in the very far distance (Crown copyright: Photograph T409–L7).

- meteorological controls on snowmelt, discharge and sediment flux (Hardy, 1996)
- sediment dispersal into lake C-2 (Retelle, 1996)
- the physical limnology of the lakes and of adjacent Taconite Inlet (Ludlam, 1996a, b)
- the near surface sedimentary record (Zolitschka, 1996; Ludlam *et al.*, 1996)
- the climatic signal in the sediments (Hardy *et al.*, 1996) and
- the environmental records preserved in the sediments (Lamoureux & Bradley, 1996; Douglas *et al.*, 1996).

Table 1. Principal factors influencing the sedimentary record of Taconite Inlet lakes

1. Weather and climate
    - Snowfall total amount, distribution
    - Snowmelt rate (especially maximum) & duration: f{radiation, temperature}
    - Glacier melt rate (especially maximum) & duration: f{radiation, temperature}
    - Rainfall timing, rate, amount
2. Within-watershed processes
    - Discharge: f{snowmelt rate, rainfall rate, active layer melt rate, gradient}
    - Sediment flux (stream channels): f{sediment availablity, discharge}
    - Sediment flux (slopes): f{slopewash, slope stability, gelifluction}
    - Primary productivity (land): f{climate, light, nutrients, substrate stability}
    - Primary productivity (lake): f{temperature, light, nutrients, ice cover}
3. Within-lake processes
    - Sediment dispersal: f{discharge, water stratification, ice conditions, outflow rate, lake circulation, wind speed}
    - Sediment re-deposition: f{slope stability, bioturbation}

Table 2. Characteristics of lakes in the Taconite Inlet region

1. Lake	2. Elevn. (m)	3. Lake area (km^2)	4. Max. depth (m)	5. Watershed area (km^2)	6. Basin relief (m)	7. Ratio (#5:#3)
C1	4	1.1	65	3.7	<100	3.4
C2	1.5	1.8	84	26.6	$\sim$1200	14.8
C3	10	1.7	51	10.8*	$\sim$880	6.4*

* If the entire Taconite River drainage is considered, watershed area 260 km^2 and ratio $\approx$153. Today, very little of the Taconite River discharge enters the lake and the principal inflow is from the drainage basin to the east of the lake.

Late Holocene climatic records from the High Arctic

General circulation models of the atmosphere with enhanced greenhouse gas concentrations have been widely used to predict future climate changes (e.g. Mitchell *et al.*, 1990). Although models often differ in their geographic details, they are unequivocal in pointing to high polar latitudes as the area likely to experience the greatest changes in climate as we enter the 21st century. In view of these predictions, it is appropriate to ask: what is the record of natural climate variability on which anthropogenic changes will be superimposed?

Ironically, our knowledge of past climate variability in polar regions is generally limited to only a few decades of instrumental records. In the Canadian Arctic Islands, for example, there were virtually no meteorological measurements before 1950. Thus, we have an extremely short perspective on natural climate variability in this area. Furthermore, many of the paleoclimate proxies which are widely used elsewhere to reconstruct past climate on the interannual timescale (such as tree rings and historical records) are not available in polar regions. So far, only ice cores have provided high resolution (i.e. annually resolved) paleoclimate information from the Arctic. There are three ice core sites in the Canadian Arctic: Devon Island Ice Cap, Agassiz Ice Cap, Ellesmere Island, and Meighen Ice Cap, Meighen Island. The core from Meighen Island consisted largely of superimposed ice and does not provide annual resolution, making dating of the core very uncertain. Wind scouring on the Agassiz Ice Cap has resulted in an incomplete record, making interpretation of the oxygen isotope record from this site difficult (Fisher *et al.*, 1983) though 'stacking' of several well-dated records improves the signal to noise ratio (Fisher & Koerner, 1994; Fisher *et al.*, 1995). Oxygen isotopic data from the Devon Island ice core indicates a mid-Holocene temperature maxima, though the picture is

Table 3. Lake C2 observation and sampling program

	Observations/Sampling	Recording interval	Period of record[2]
1. Meteorology			
1.1 Lake site (Station Delta: 7 m a.s.l.)			
	Ground temperature (50 cm)	hourly	1991, 1992
	Surface temperature	hourly	1992
	Air temperature	hourly	1990-92
	Snowpack temperatures	10 minute	1992
	Relative humidity	hourly	1990-92
	Wind speed & direction	hourly	1990-92
	Air pressure	hourly	1990-92
	Shortwave radiation (K↓)	hourly	1990-92
	Albedo (K↓/K↑)	hourly	1991, 1992
	Longwave radiation (L↓)	hourly	1991, 1992
	Net (allwave) radiation	hourly	1991, 1992
	U-V (B) radiation	hourly	1992
	Precipitation (Total w.e.)	twice daily	1990-92
	Cloud amount and type	hourly (irreg.)	1990-92
1.2 Mountain site (Station Echo Peak: 520 m a.s.l.)			
	Air temperature	hourly	1991, 1992
	Ground temperatures	hourly	1992
	Surface temperature	hourly	1992
	Snowpack temperatures	10 minute	1992
	Relative humidity	hourly	1991, 1992
	Wind speed & direction	hourly	1991, 1992
	Shortwave radiation (K↓)	hourly	1991, 1992
	Albedo (K↓/K↑)	hourly	1991, 1992
	Longwave radiation (L↓)	hourly	1991, 1992
	Net (allwave) radiation	hourly	1991, 1992
	Precipitation (Total w.e.)	irregularly	1990-92

[2] Inclusive dates for 24 hour meteorological data sets:
1990: June 8-July 28
1991 (Delta): May 30-July 12
(Echo): May 31-July 11
1992 (Delta): May 17-August 8
(Echo): May 19-August 7.

complicated by the possibility that the ice cap became thinner from the early to the mid-Holocene and then became thicker, leading to changes in $\delta^{18}O$ that may be partly, or entirely, the result of changes in the ice cap elevation (Fisher & Koerner, 1981; Koerner & Fisher, 1985).

Melt features provide a more direct index of summer temperature, and studies on the Devon Island ice core clearly show cold conditions (few melt layers) during the 16th–19th centuries, followed by warming in the 20th century (Koerner, 1977). However, the melt record there only spans a few centuries. In the Agassiz core, melt features have now been studied for the entire Holocene (Koerner & Fisher, 1990) and these reveal much warmer conditions in the early Holocene than in the last 4000 years. Indeed, there is considerable evidence that the late Holocene climate of the High Arctic has been quite different from earlier periods. After reviewing ice core and all other sources of paleoclimatic information from the Queen Elizabeth Islands, Bradley (1990) concluded:

> *'Temperatures declined from ~ 3000 B.P., culminating in exceptionally low temperatures from ~ 100–400 B.P....this may have been the coldest period*

Table 3. Continued. Lake C2 observation and sampling program

	Observations/Sampling	Recording interval	Period of record[2]
2. Hydrology and sediment flux[3]			
2.1 Lake C2 Main Inlet Stream			
	Stage height	hourly/irreg.	1990
		continuous	1991, 1992
	Discharge	irregularly	1990-92
	Suspended sediment (SSC)	irregularly	1990-92
	Electrical conductivity	2-3 times/day	1990-92
	Water temperature	2-3 times/day	1990-92
4. Limnology			
4.1 Physical limnology[4]			
	Secchi disk readings	daily/irreg.	1990-92
	Temperature profiles	daily/irreg.	1990-92
	Conductivity profiles	daily/irreg.	1990-92
	Dissolved oxygen	daily/irreg.	1990-92
	PAR	daily/irreg.	1990-92
	Transmissivity	daily/irreg.	1990-92
4.2 Biological limnology			
	Diatom collections from algal mats, rocks, streams		1990-92
	Planktonic, benthic samples		1990-92
	Productivity		July 1990

[3] Streamflow measurement periods: 1990: June 9 to July 28; 1991: June 4 to July 12; 1992: June 22 to August 9. Similar measurements at other inflowing streams, and at the Lake C2 outlet stream, were made on irregular intervals in all three years.
[4] Measurements made at a network of sites until dangerous ice conditions prevented survey

> *in the entire Holocene... The period since ~A.D. 1925 has been the warmest for at least 1000 years and perhaps several thousand years...modern climate may therefore be characteristic of the early to mid-Holocene and atypical of conditions which prevailed for much of the last few thousand years.'*

These conclusions need to be tested, but if correct, studies of laminated sediments spanning the last 1000–2000 years will provide information about a period of extraordinary environmental change in the Arctic – a period of declining temperatures to the coldest epoch of the Holocene followed by a quite abrupt shift to conditions not experienced for thousands of years. Indeed, recent research on southeastern Ellesmere Island provides evidence that the last century has witnessed limnological changes which are unique in the Holocene (Douglas *et al.*, 1994).

The Taconite Inlet region

Physiography

Taconite Inlet is a north-facing fiord on the north coast of Ellesmere Island. Local relief (part of the Challenger Mountain Range) extends to ~1250 m a.s.l. and the area is extensively glacierized. To the south, the Grant Land Mountains (which are largely ice-covered) increase in elevation to >2500 m in places, isolating the north coast from the interior of Ellesmere Island. Northward drainage of ice from the Grant Land Mountains occurs via several major northward flowing rivers, one of which (the Taconite River) drains into Taconite Inlet.

Glaciation levels rise sharply away from the coast; indeed glaciation levels along the coast of northern Ellesmere Island are among the lowest in the world and ice shelves are extensive in the region (Miller *et al.*, 1975). Ice shelves in this region form from fast ice (sea ice) on which snow and superimposed ice have accumulated, and beneath which freshwater (from rivers discharging into the fiords) has frozen onto the base. They may reach thicknesses of >50 m and extend many miles from the shore, restricting the interchange of water between the Arctic Ocean and the fiords (Jeffries, 1992). Ice shelves appear to have formed in this region in the late Holocene, since many pieces of driftwood dating >3000 B.P. have been found on isostatically uplifted beaches behind the present day ice shelves, whereas younger driftwood has not been found, except in Clements Markham Inlet and Colan Bay to the east (Figure 3). At present, the mouth of Taconite Inlet is partly blocked by an ice shelf to the west of Bromley Island, and by an ice shelf extending almost across the mouth of M'Clintock Inlet (Figure 1). It is possible that an ice shelf extended across the entire mouth of the fiord at some time during the late Holocene.

Ice shelf formation may have resulted in stable density stratification of the water column in basins of Taconite Inlet that are now isolated lakes before they became separated from the sea. Hence, the characteristically laminated sediments found in meromictic lakes of the region today may date from a period of restricted water circulation prior to isostatic emergence, not simply from the time of isolation. For example, Taconite Inlet is today strongly stratified (Ludlam, 1996a) and bottom waters are anoxic, minimising bioturbation of the sediments; hence there are varved sediments forming in the fiord environment today. If the ice shelves were to break up, opening the fiord to greater exchange with oxygenated water from the Arctic Ocean, it is likely that subsequent sediments would not be laminated.

Geology and glacial history

The Taconite Inlet region is composed of late Proterozoic to early Ordovician carbonates, quartzites, mudrocks and small amounts of mafic and siliceous volcanic deposits of the Challenger Mountains Supergroup. The rocks formed in a basin within the Pearya composite terrane, which has Appalachian-Caledonian affinities. Additionally, the Challenger Mountains Supergroup are unconformably overlain by carbonate rocks of the Carboniferous to Cretaceous Sverdrup Basin, and scattered outcrops of these rocks are found in the upper Taconite River valley (Trettin, 1987).

Regional ice cover has been far more extensive in the past; Lemmen (1989) reports erratics on summits of the Marvin Peninsula (to the east) up to 925 m a.s.l. and it is likely that ice cover was similarly extensive in the Taconite Inlet region. A pronounced weathering break can be identified at ~ 350 m on the eastern side of Taconite Inlet, above Lake C2, indicating the upper limit of a large outlet glacier in the area (Figure 4). Regional studies suggest that late Wisconsinan ice cover was not extensive, with glacier termini less than 20 km from present day ice limits (Bednarski, 1986; Lemmen, 1989; Evans, 1990; England, 1992). Nevertheless, isostatic depression and subsequent emergence has resulted in numerous raised marine features (shorelines and deltaic deposits) throughout the Taconite Inlet area. The Holocene marine limit in the area of Lake C2 is >75 m a.s.l., but the exact elevation is unknown and no post-glacial uplift curve exists for this region. By analogy with similar north-facing fiords, it seems likely that the marine limit along the outer coast is 65–75 m, increasing to 110–120 m in the (ice-free) southern part of Taconite Inlet (cf. Disraeli Fiord and M'Clintock Inlet [Lemmen, 1989] and Clements Markham Inlet [Bednarski, 1986]). Regional deglaciation began around 9500 B.P. (Lemmen, 1989).

Climate

Taconite Inlet climate can be characterised as a maritime polar desert (Bovis & Barry, 1974; Maxwell, 1981). Monthly mean temperatures at the nearest weather station (Alert: 82°30′ N, 62°20′ W, 63 m a.s.l., ~ 230 km east of Taconite Inlet) range from ~ −33 °C (February) to ~ +4 °C (July) (Maxwell, 1982). Annual melting degree day totals (cumulative temperatures above 0 °C) at Alert average ~ 203. Annual precipitation is ~ 156 mm, mostly in the form of snow, though this may be underestimated by at least 20% (Bradley & England, 1974). During summer months the coastal zone is frequently influenced by low stratus clouds (<300 m) and/or fog, associated with temperature inversions. These clouds reduce incoming solar radiation receipts at lower elevations so that temperatures in the upper drainage basins are often higher than in those parts of the Inlet nearer to sea level. This exerts an important control on snowmelt distribution, particularly in the early summer. Temperature inversions are present almost all the time during winter months, and are common even in mid-summer (Bradley *et al.*, 1993).

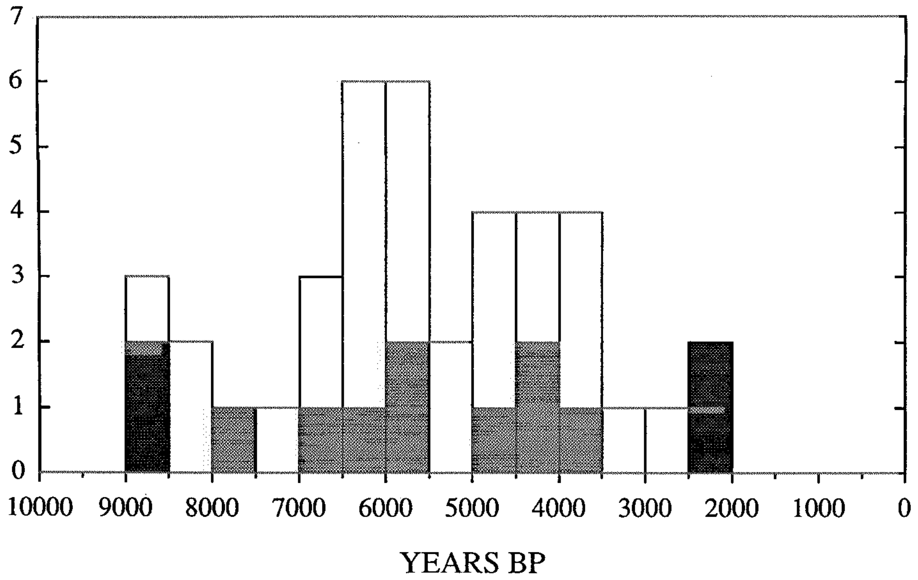

Figure 3. Histogram of driftwood ^{14}C ages from north coast of Ellesmere Island. Shaded values indicate dates from Clements Markham Inlet and Colan Bay, which are the inlets farthest to the east.

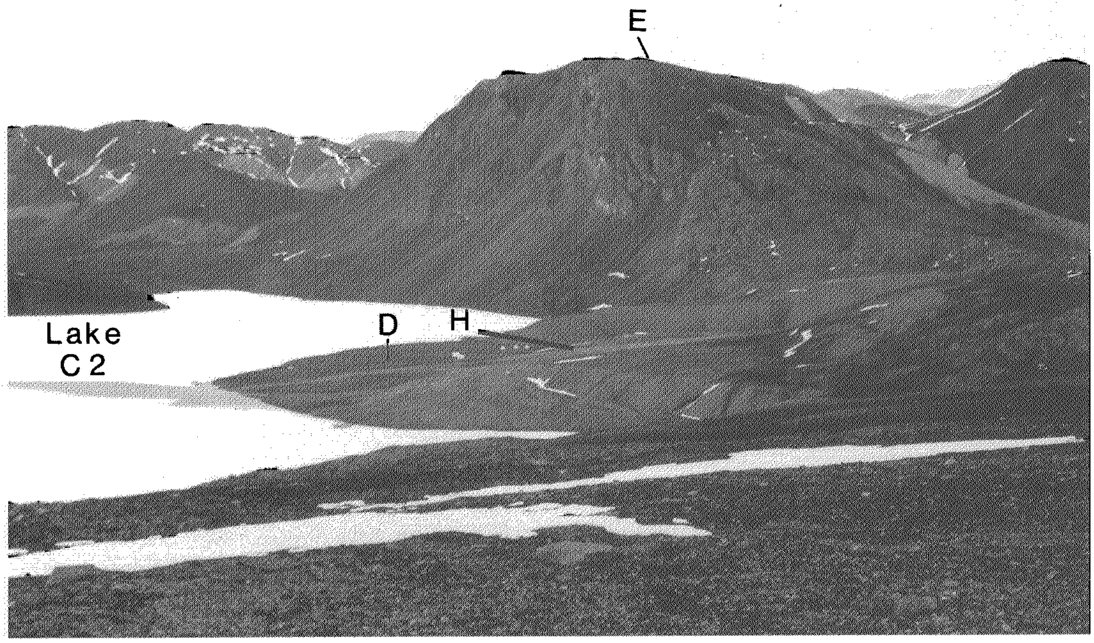

Figure 4. Photograph of Lake C2, looking from southwest, towards the Delta and Echo Peaks, from the hill separating Lakes C2 and C3. Arrows indicate locations of Delta (D) and Echo Peak (E) meteorological station sites and hydrological monitoring station (H).

Taconite Inlet lakes

A summary of the main characteristics of the Taconite Inlet lakes is given in Table 2. Here we provide some comments on the individual lakes and their associated drainage basins (Figure 2). Anaerobic conditions have been recorded close to the sediment water interface in all three lakes; lakes C1 and C2 are anoxic below 16 and

20 m, respectively. In Lake C3, anoxic conditions can extend upwards to 42 m depth, but occasionally traces of oxygen have been found to a depth of 49.2 m, the maximum recorded depth (Ludlam, 1994b). However, relatively few measurements were made in Lake C3 and the bathymetry is not well mapped.

Lake C1

The northernmost lake, C1, (termed 'Lake C' by Hattersley-Smith *et al.*, 1970) has the smallest of the three drainage basins and receives very little runoff; what there is enters the lake largely by overland flow from snowmelt around the lake, or from one small (snow-fed) stream (Figure 5). The lake appears to be ice-covered throughout the year, with only a marginal moat (5–10 m wide) developing each summer. It is possible that in exceptionally warm summers there may be more ice loss, but since the area is very rarely visited, there are no observations indicating ice-free, or essentially ice-free conditions. One unusual feature we observed was the presence of several small (<0.5 m diameter) holes through the ice in early June, when the rest of the lake was covered by ice ~ 1.3 m thick and snow ~ 0.5 m deep. Such holes (at the center of star-shaped cracks in the ice) are also visible on air photographs of this lake taken in the 1950s (but not visible on lakes C2 or C3) and so appear to be a characteristic feature of lake C1. The holes we observed were not simply new melt holes; the snowcover was deep and had not started to melt when the holes were first observed. The ice was otherwise covered by highly reflective snow with temperatures at the base of the snowpack (on the ice) ranging from −2 °C to −14 °C. In some cases the holes were partially covered by a snow bridge, making them somewhat hazardous. We have no good explanation for these holes, but note that the lake contains warm water >8 °C from 7–30 m depth (reaching a maximum of 11.5 °C at ~ 16 m; Ludlam, 1994b) and we observed gas bubbles (probably methane) rising to the surface for a considerable period after we extracted sediment cores from the lake. We speculate that there may be certain locations where warm water is carried to the surface, perhaps associated with plumes of gas, thereby limiting ice growth in those zones. Possibly a few melt cracks which developed late in the previous summer are kept open in this way, perhaps under an insulating blanket of snow. If this process is responsible for the holes, presumably, the entrainment of warm water by rising gas bubbles is sufficiently localised that widespread disturbance of the lake stratification does not occur.

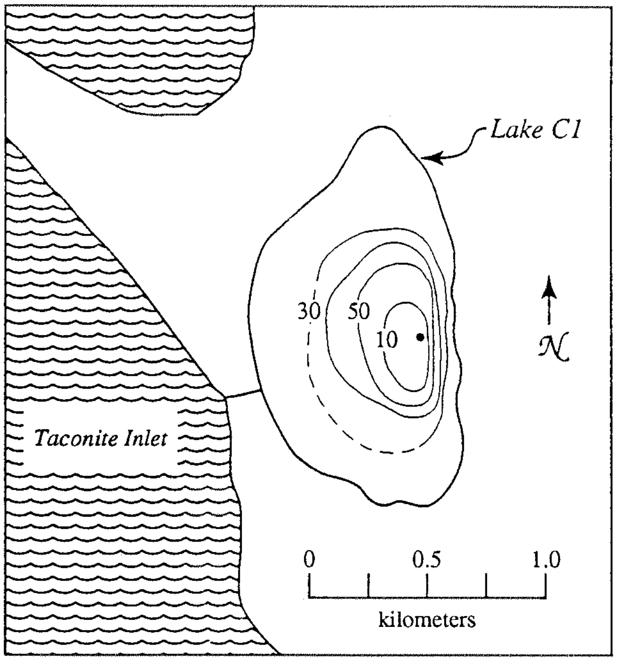

Figure 5. Map of Lake C1, showing approximate bathymetry, coring sites, and outlet to Taconite Inlet. There are no major inflowing streams.

Lake C2

Lake C2 is a glacially over-deepened basin, separated from Taconite Inlet itself by a moraine or till-mantled bedrock to the north and west of the lake. The drainage basin is mountainous, with extremely steep slopes, often at the angle of rest. The lake receives runoff from glaciers upstream, as well as snowmelt from surrounding slopes. However, since the glaciers are small and cold-based, little sediment is generated by the ice. The bulk of water and sediment entering the lake does so via the primary inlet to the east (Figure 6). A very large delta was formed as this river entered (the formerly more extensive) Taconite Inlet (Figure 4); this delta is now exposed as a series of raised terraces above the lake. Some of the sediment entering the lake today is material being eroded from these early Holocene deposits, which creates problems in ^{14}C dating of organic materials in the lake sediments. Upstream of the delta, the river passes through very confined canyon-like sections which are easily blocked by snow avalanches and/or slope debris. Rapid changes in discharge, observed early in the season, indicate that the river is subject to periodic ephemeral damming, which can influence sediment transport downstream.

Lake C3

The Taconite River drains an area of ~ 250 km^2 and flows through an extensive sandur before debouching into Taconite Inlet. The river today is very small, but judging by the size of the sandur, it must have been much more extensive in the past (early Holocene?). At some time, the Taconite River must have discharged a large volume of water (and sediment) into Lake C3 because many abandoned channels of the sandur form the southwestern margin of the lake. Nowadays, however, only a small distributory of the Taconite River enters Lake C3, and this is only a few meters from the contemporary outlet stream (Figure 7). The main river entering Lake C3 today, drains terrain similar in relief to that of the main drainage into Lake C2. Unlike Lakes C1 and C2, the water of Lake C3 is essentially fresh and chemical stratification is weak. In all probability, the lake was probably flushed clear of marine water by the large influx of glacier meltwater from the Taconite River at some time in the past.

Age of the Taconite Inlet lakes

Taconite Inlet was occupied by ice until the early Holocene when recession and isostatic uplift led to emergence of the present day coastal zone. All three lakes in Taconite Inlet (Figure 1) are located (at <5 m a.s.l.) well below the marine limit and so became isolated in the late Holocene. However, present day lake elevations may not be the critical factor in determining the exact time of isolation, if significant down-cutting has occurred through the outlet. The stream draining Lake C2 passes through a narrow channel which is incised 10–15 m in till (or till-mantled bedrock) and a similar incised channel separates Lake C1 from Taconite Inlet. If there has been 10–15 m of downcutting since lake isolation (i.e. the downcutting has more or less kept pace with isostatic uplift) the lakes may be several thousand years older than their present elevations indicate. For example, if the uplift curve from inner Clements Markham Inlet (150 km to the east) is applied to this area (Bednarski, 1986) the modern lake elevations would indicate isolation within the last ~ 1000 years. However, if the lakes were formerly 10–15 m higher, this would indicate isolation 3000–4000 years B.P. Support for an earlier time of isolation is provided by a ^{14}C date on dissolved inorganic carbon from the monimolimnion of Lake C1 which was 4940 ± 90 B.P. (M. Jeffries, personal communication). However, as discussed by Ludlam (1996a) it is likely that lakes C-1, C-2 and C-3 all became meromictic before complete separation from Taconite Inlet so that the accumulation of laminated sediment under anoxic conditions probably pre-dates the time of lake isolation in each case.

The Taconite Inlet Lakes Project

A three year research program, focused on Lake C2 and its watershed, was initiated in 1990. As stated earlier, the objective was to obtain an understanding of the paleoclimatic signal in varved sediments from the lake by studying the primary controls on sediment flux to the lake, and sediment transport within the lake. Table 3 provides details of the observational program.[1] Solar radiation and other meteorological parameters were recorded at the Delta site (Figures 4 and 6) in all three summers of the project. A second station, at 520 m elevation on Echo Peak (Figure 4) was established after the first year to obtain information on meteorological conditions in the upper section of the drainage basin, above the frequent low stratus cloud layer. Echo Peak station was located close to the median elevation of the watershed and frequently recorded temperatures higher than at the Delta site. Hydrological measurements and sediment flux samples were made on the main stream entering Taconite Inlet, 100 m upstream of the Delta meteorological station. Further discussion of these observations is given in Hardy (1996). Meteorological data from the Lake C2 stations were compared with the longer records at Alert to provide a 40 year perspective on climatic conditions in the region. These comparisons (Hardy *et al.*, 1996) show that sediment flux was strongly related to daily temperatures above 0 °C.

Sediment traps were deployed in an array in front of the main delta of Lake C2; certain traps were recovered after significant runoff events, others were sampled on a seasonal basis. In addition, regular measurements of Secchi disk visibility were made as the season progressed, and profiles of temperature, conductivity, dissolved oxygen, transmissivity (horizontal absorption) and PAR (photosynthetically active radiation) were made at a network of sites across the lake with a Seacat SBE19 profiler (Seabird Electronics).

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[1] Further details, including photographs and data files, can be accessed via the Taconite Inlet Home Page on the World Wide Web (see http://www.geo.umass.edu).

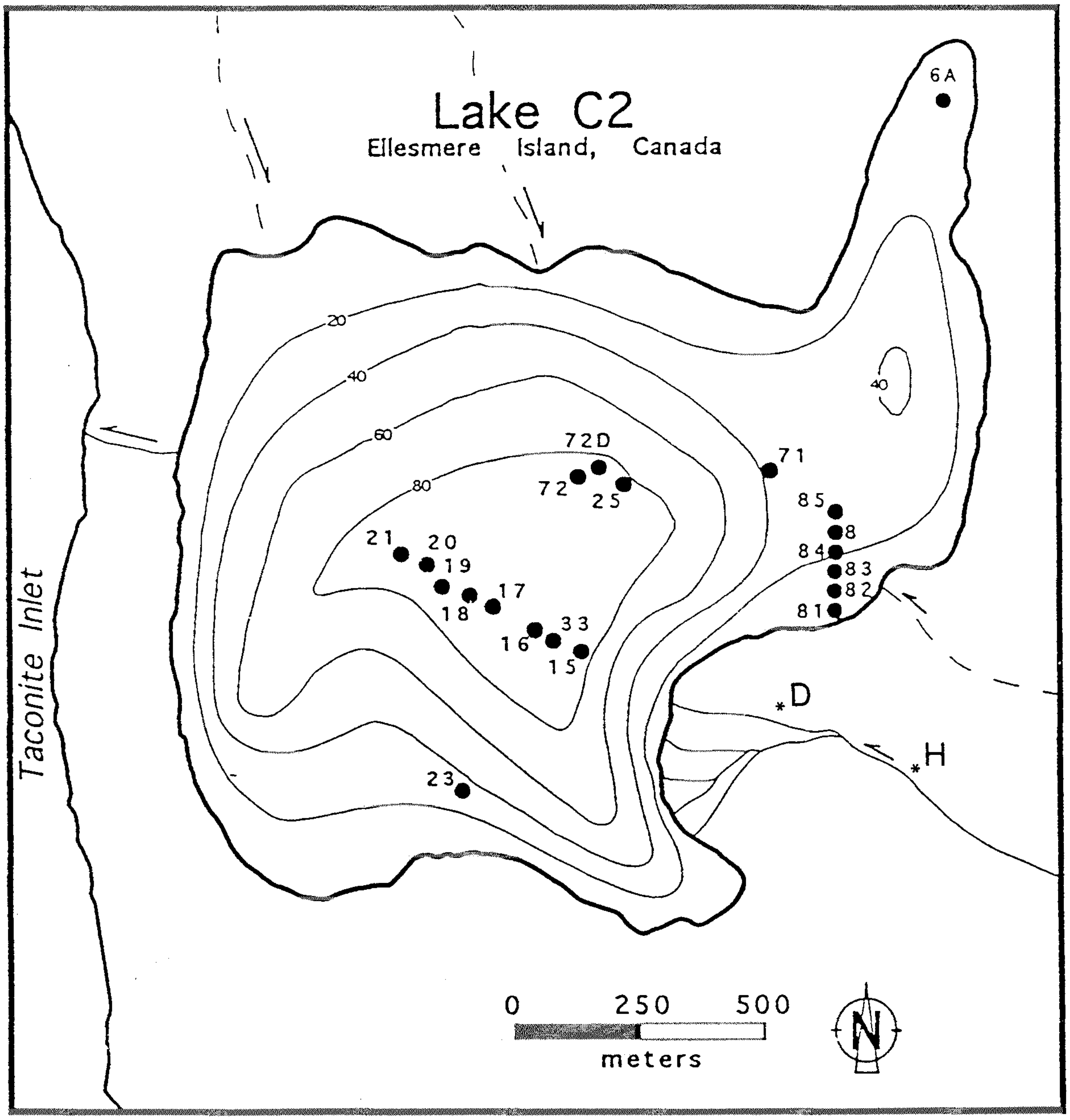

Figure 6. Map of Lake C2, showing bathymetry, coring sites, meteorological station (D) and hydrological station (H), principal inflowing streams, and outlet to Taconite Inlet (cf. Figure 4).

Further details of these observations are provided in Retelle (1996) and Ludlam (1996b).

A set of short sediment cores were recovered along a transect from the inlet to the outlet of the lake, together with other cores along transects perpendicular to this transect, using both Ekman dredges and a KB corer. Detailed studies of these cores was carried out to determine if the laminations could be correlated from one location in the lake to another, and if the laminations were indeed annual. The results demonstrated the sediments are indeed varved and that there is strong coherence between the varve thickness from widely separated cores within the lake; details of this work are given in Zolitschka (1996). Sediment flux to the lake, 'predicted' by the temperature record at Alert, closely parallels variations in mean thickness of the varves over the last 40 years (Hardy *et al.*, 1996) enabling a long record of lamination thickness (Lamoureux, 1994) to be interpreted as a record of summer temperature variations.

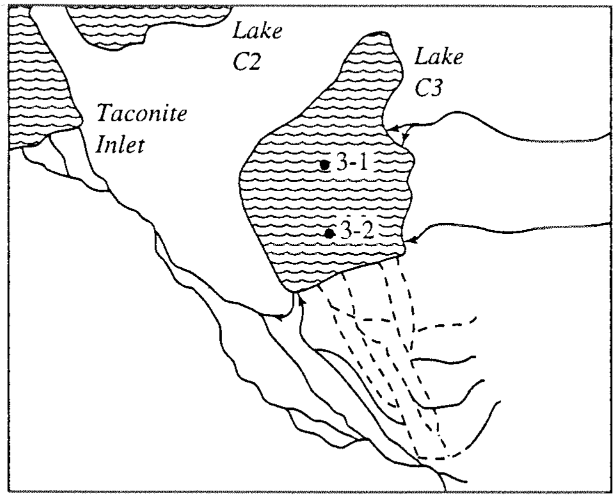

Figure 7. Map of Lake C3, showing coring sites, streams. Site 3-1 = 56.5 m water depth; 3-2 = 49 m. Taconite Inlet (T.I) and Lake C2 are indicated. Note extensive braiding of Taconite River and former channels of river (dashed) which do not, at present, carry water into Lake C3. Main inflow from Taconite River is now in the southwest corner, within meters of the main outlet.

A set of sediment cores (each ∼ 1 m in length) was recovered along a transect across the lake floor, from below the oxycline to above it (Figure 6). We hypothesise that the preservation of varved sediments is restricted to the anoxic zone beneath the oxycline (where bioturbation is minimal), and that the presence or absence of laminations in shallow water sediments indicates changes in the depth of the oxycline over time. The results of this work, and of the paleoclimatic record in the laminated sediments from these cores, are discussed in Lamoureux & Bradley (1996).

Studies of the modern diatom ecology of the lake and streams entering the lake, were carried out throughout the project. These studies provided insight into the recent paleoenvironmental record represented by the diatom flora in the sediments and further discussion of this aspect of the study is given in Ludlam *et al.* (1996). The diatom record in a core which extends back to the time when lake C2 was part of Taconite Inlet is given in Douglas *et al.*, 1996.

Collectively, these studies provide a comprehensive evaluation of the modern environment in the Taconite Inlet area in general, and the Lake C2 watershed, in particular. By taking a systems approach, we have tried to assess the role of different factors which determine the inter-annual variations of sediment accumulation in the lake. Process-based studies are especially important in the Arctic, as there are only a few, widely separated, long-term records with which to calibrate sedimentary records. By measuring contemporary processes, a quantitative understanding of the climatic controls on sedimentation can be achieved, thereby strengthening paleoclimatic interpretations of the sedimentary record.

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