Géographie physique et Quaternaire

Stratigraphy and Sedimentology of Coastal Lacustrine Basins, Northeastern Ellesmere Island, N. W. T.
Stratigraphie et sédimentologie de bassins lacustres côtiers, nord-est de l'île d'Ellesmere, T.-N.-O.
Stratigraphie und Sedimentologie an der Küste liegender Seen-Becken, im Nordosten der Ellesmere-lnsel, Nordwest-Territorien

Michael J. Retelle

Résumé de l'article

Les carottes de sédiments recueillies dans trois bassins lacustres côtiers du Haut Arctique sont composées d'une séquence de sédiments glacio-marins recouverte par des sédiments lacustres stratifiés d'aspect laminaire à massif. La mise en place des sédiments glacio-marins s'est effectuée au moment où les bassins étaient sous le niveau de la mer. Après l'emersion des bassins, les sédiments lacustres se sont déposés dans chacun des bassins. Le faciès de transition entre les unités lacustre et marine représente un intervalle d'individualisation au cours duquel l'eau de mer a été retenue sous des lentilles d'eau douce. Les données sédimentologiques et fauniques tirées des carottes démontrent que les rentrants étaient fermés et que la sédimentation fluviatile était minimale au pléni-glaciaire (ca 8000-8200 BP). Les augmentations subséquentes de la teneur en sable et du contenu macrofaunique témoignent de l'accroissement de la mobilité de la glace marine et de la quantité d'eaux de fonte au cours de l'Holocène moyen. Le refroidissement survenu au cours de l'Holocène supérieur s'est reflété par une diminution des matériaux transportés par les glaces et par une augmentation des sédiments de surface lacustres à stratification diffuse.

STRATIGRAPHY AND SEDIMENTOLOGY OF COASTAL LACUSTRINE BASINS, NORTHEASTERN ELLESMERE ISLAND, N. W. T.*

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ABSTRACT   Sediment cores recovered from three high arctic coastal lake basins contain a sequence of glaciomarine sediments overlain by laminated to massive-bedded lacustrine sediments. Glaciomarine sediments were deposited while the basins were isostatically depressed below sea level. Subsequent to emergence of the basin from the sea, lacustrine sediments accumulated in each basin. A transitional facies between the marine and lacustrine units represents an isolation interval during which trapped sea water lay beneath a freshwater lens. Sedimentological and faunal evidence from sediment cores demonstrates that embayments were closed and fluvial sedimentation was minimal during the glacial maximum (ca. 8000-8200 BP) Subsequent increases in sand content and macrofaunal abundance reflects increases in mobility of sea ice and fluvial input during the middle Holocene. Late Holocene cooling trends are demonstrated by decreases in ice rafted material and an increase in diffuse bedding in lake surface sediments.

RÉSUMÉ   *Stratigraphie et sédimentologie de bassins lacustres côtiers, nord-est de l'île d'Ellesmere, T.N.-O.* Les carottes de sédiments recueillies dans trois bassins lacustres côtiers du Haut Arctique sont composées d'une séquence de sédiments glacio-marins recouverte par des sédiments lacustres stratifiés d'aspect laminaire à massif. La mise en place des sédiments glacio-marins s'est effectuée au moment où les bassins étaient sous le niveau de la mer. Après l'émersion des bassins, les sédiments lacustres se sont déposés dans chacun des bassins. Le faciès de transition entre les unités lacustre et marine représente un intervalle d'individualisation au cours duquel l'eau de mer a été retenue sous des lentilles d'eau douce. Les données sédimentologiques et fauniques tirées des carottes démontrent que les rentrants étaient fermés et que la sédimentation fluviatile était minimale au pléni-glaciaire (ca 8000-8200 BP). Les augmentations subséquentes de la teneur en sable et du contenu macrofaunique témoignent de l'accroissement de la mobilité de la glace marine et de la quantité d'eaux de fonte au cours de l'Holocène moyen. Le refroidissement survenu au cours de l'Holocène supérieur s'est reflété par une diminution des matériaux transportés par les glaces et par une augmentation des sédiments de surface lacustres à stratification diffuse.

ZUSAMMENFASSUNG   *Stratigraphie und Sedimentologie an der Küste liegender Seen-Becken, im Nordosten der Ellesmere-Insel, Nordwest-Territorien.* Sediment-Proben, die aus drei Seen-Becken der Hoch-Arktis-Küste gewonnen wurden, enthalten eine Folge glaziomariner Sedimente, welche von blättrigen bis massiv gebetteten Seesedimenten überlagert werden. Die glaziomarinen Sedimente wurden abgelagert, während die Becken isostatisch unter den Meeresspiegel gedrückt waren. Nach dem Auftauchen der Becken aus dem Meer lagerten sich in jedem Becken Seesedimente ab. Die Übergangs-Fazies zwischen den Meeres- und Seeeinheiten stellt ein Isolations-Intervall dar, während welchem Meeres-Wasser unter einer Süßwasser-Linse gefangen war. Die aus den Sediment-Proben gewonnenen Sediment- und Fauna-Daten zeigen, daß die Einsprünge geschlossen waren und die Fluß-Sedimentierung minimal während des glazialen Maximums (ca. 8000-8200 v.u.Z.). Anschließende Zunahmen an Sand-Gehalt und ein Überfluß der Makro-Fauna spiegeln Zunahmen in der Mobilität des Meeres-Eises und der Schmelzwassermenge während des mittleren Holozän. Die Abkühlung während des späten Holozän zeigt sich in der Abnahme der durch das Eis transportierten Materialien und in der Zunahme diffuser Schichtung in den Oberflächen-See-Sedimenten.

INTRODUCTION

Relative sea level changes caused by the glacio-isostatic depression and uplift of coastal zones may be manifested in sedimentary sequences contained in coastal lake basins. Sediment cores recovered from these "isolation basins" may reveal a continuous record of environmental changes during periods of marine submergence, isolation of the coastal lake basin, and subsequent lacustrine sedimentation.

Studies of the marine-lacustrine sequences may yield important information regarding the duration of marine sedimentation (MANGERUD, 1985) and/or age of deglaciation of the lake basins (BLAKE, 1981). It may also be possible to reconstruct a relative sea level history by dating sediment organics at lacustrine-marine emergence levels (KALAND et al., 1983) or more accurately by accelerator dating of in situ molluscs at, or just beneath emergence contacts in the cores (RETELLE et al., in review). Lastly, the sediment cores may yield an important high resolution record of climatic change, seen in stratigraphic, textural, faunal, and geochemical evidence from the sediment cores.

The purpose of this paper is to investigate the stratigraphy and sedimentology of glaciomarine-lacustrine sequences from coastal lake basins on northeastern Ellesmere Island, Arctic Canada. Evidence from sediment cores from three lakes will be used to reconstruct aspects of paleoenvironments and of climatic changes during the Holocene.

METHODS

Fieldwork was conducted in 1981 and 1982 as part of a study of the Quaternary glacial and marine history and environments of the Robeson Channel area (RETELLE, 1985 and in press). Piston cores of the lake bottom sediments were recovered using a modified Livingstone corer with a stainless steel core tube 1.3 m long and 4.5 cm in diameter. Magnesium-zirconium drive rods were used with the corer, which retrieved up to 4.8 m of sediment using repetitive drives down the same borehole. Core sections were extruded in the field, wrapped in plastic and aluminum foil. and stored in trays in insulated core boxes until returned to the lab. The cores were stored in a dark room at + 4°C. Sediment in plastic paleomagnetic sampling cubes was used for grain size analysis, loss-on-ignition, and organic carbon determinations. Loss-on-ignition was measured after drying the sample overnight at 65°C, followed by combustion at 450°C for 2 hours. Organic carbon determinations were made using the modified Walkley-Black titration method (GAUDETTE et al., 1974).

Sediment laminations were counted under a binocular microscope while the core was still moist. Thin sections were prepared from specific levels in the cores using standard thin sectioning techniques following vaccum impregnation of air-dried sample sections with Hillquist impregnation epoxy.

Water samples, recovered from the lakes with a Kemmerer sampler, and from inflowing streams with Nalgene bottles, were stored in opaque bottles. Temperature, pH, and alkalinity of the lake waters were measured in the field. Chloride was measured with specific ion electrode in the laboratory.

RESULTS

LOCATION AND GEOMORPHOLOGY

Three lakes, unofficially named the "Beaufort Lakes", are situated in a large south-east facing cirque basin 2 km north of Mt. Beaufort and approximately 65 km south of Alert (Fig. 1). The cirque, which opens toward Robeson Channel, is incised into the eastern edge of the Hazen Plateau, which is made up of Lower Paleozoic flysch sediments of the Imina Formation (TRETTIN, 1971).

The basin is floored by till, which is exposed at the surface above the Holocene marine limit (116 m). Abundant red granitic and gneissic erratics in this drift sheet (probably of Greenland provenance) stand out in contrast to the gray-brown Imina Formation. The till was deposited during the advance of northwest Greenland ice onto northestern Ellesmere Island, tentatively $\geq$ 80,000 years BP (CHRISTIE, 1967; ENGLAND et al., 1981).

Gravelly beach sediment and interfingering deeper-water glaciomarine silts overlie till below the marine limit (Fig. 2). Abundant molluscs in life position in the silt unit include Hiatella arctica, Portlandia arctica, Astarte borealis, and Mya truncata. On gravel beaches, single and abraded shells are common. The glaciomarine sediments were deposited in an ice marginal depression or "full glacial sea" along Robeson Channel between northwest Greenland and northern Ellesmere Island ice masses which stood at their last-glacial maximum between 11,000 and 8000 BP (ENGLAND, 1983). The duration of marine sedimentation in the ice-marginal depression has not been determined, however shells from the marine limit sediments at Beaufort Lakes were radiocarbon dated at 8200 to 8000 BP (Fig. 2).

The three lakes at the field site are located at elevations of 12, 34 and 39 m asl; hereafter they will be referred to as Lakes 1, 2, and 3 in order of increasing elevation. The lakes are held in by resistant northeast-trending bedrock ridges mantled by marine silts and beach gravels.

Lake 3 is the smallest of the lakes (0.6 km x 0.3 km) and is the shallowest at ca. 12.4 m maximum depth. Inlet streams are few and small, with the largest originating from snow cornices on the northern headwall of the basin. The outlet of Lake 3 is ca. 0.3 to 0.5 m deep and flows into Lake 2 (Fig. 3).

Lake 2 is the largest of the three lakes and is the furthest from Robeson Channel. It is approximately 1.2 km long and nearly divided into two basins by a northeast-southwest trending bedrock ridge. The northwestern half of the basin is about 30 m deep and shallows to the east. Most of the watershed is drained by two streams which flow into the northwest end of Lake 2. Thus, Lake 2 has the greatest sedimentation rate of the lakes; two inlet streams have deposited delta fans into the northwestern margin of the lake.

Lake 1, at 12 m a.s.l., has a maximum depth of 22 m. Its outlet flows into Robeson Channel. The immediate drainage of this basin is small, limited to the steep headwalls surrounding the basin.
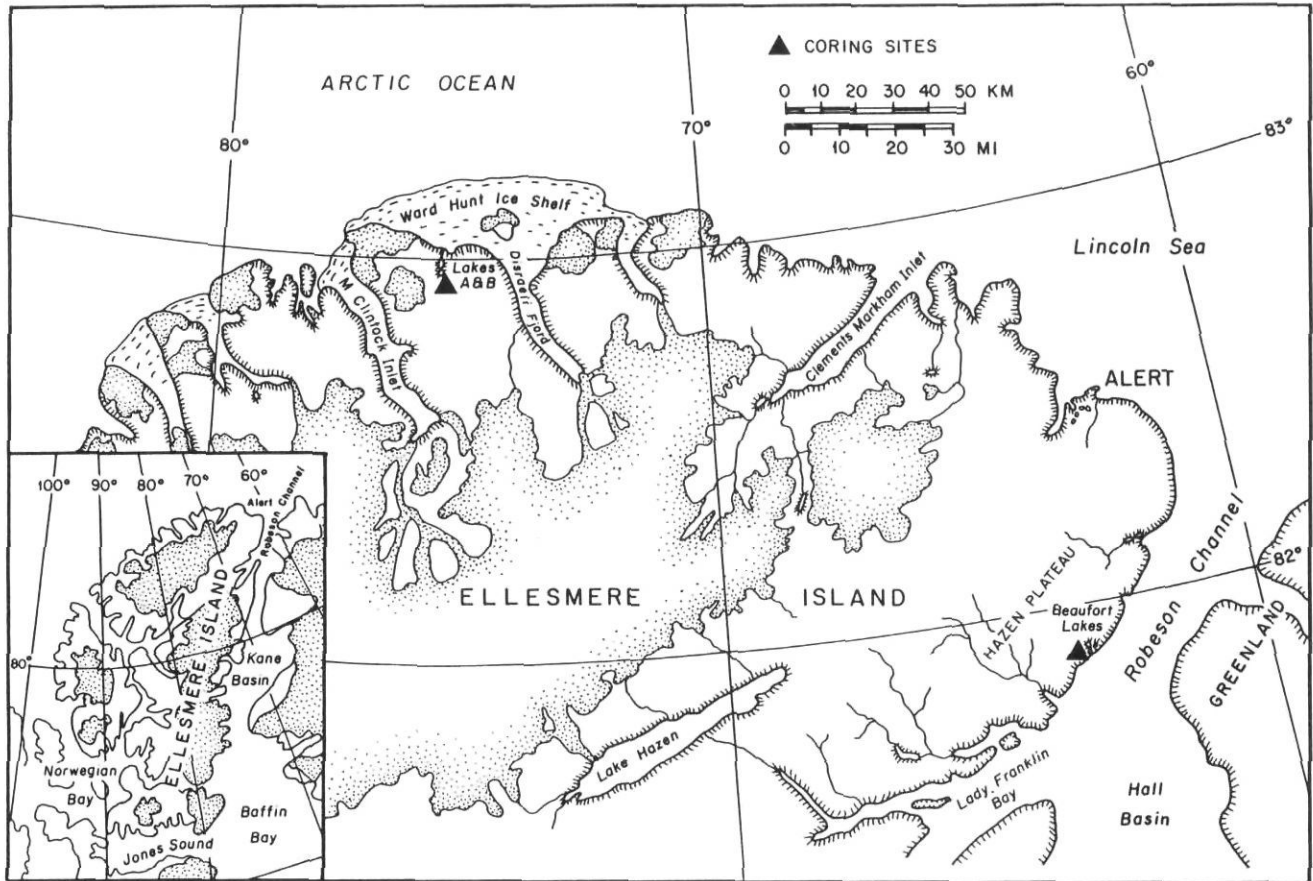
FIGURE 1. Location map of northern Ellesmere Island *Carte de localisation de l'île d'Ellesmere.*
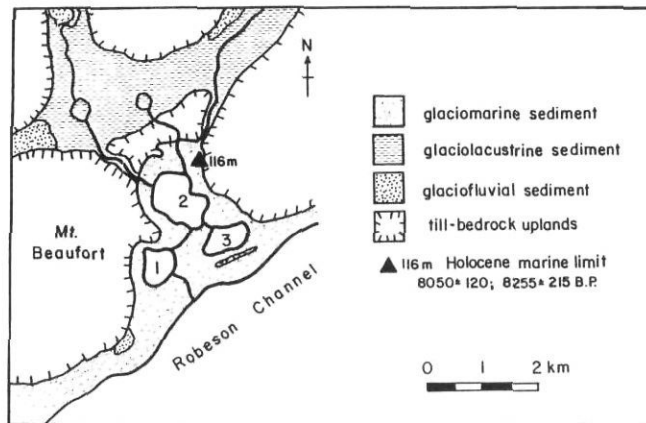

FIGURE 2. Surficial geologic map of the Beaufort Lakes coring site. Lakes 1, 2 and 3 are at elevations of 12, 34 and 39 m a.s.l., respectively.

Cartes des formations superficielles des sites de carottage aux lacs Beaufort. Les altitudes des lacs n°ˢ 1, 2 et 3 sont respectivement de 12, 34 et de 39 m a.n.m.

FIGURE 3. Photograph of a portion of the Beaufort Lakes embayment showing Lakes 1, 2 (eastern half) and 3. Arrows point to 40 m terrace that was likely the threshold to lakes 2 and 3 during emergence. View is toward the south with Robeson Channel in near background and northwest Greenland (left) and Judge Daly Promontory (right) in far background.

Photographie d'une partie du rentrant des lacs Beaufort montrant les lacs n°ˢ 1, 2 (moitié est) et 3. Cette vue vers le sud montre tout près, à l'arrière-plan, le détroit de Robeson et, dans le lointain, le nord-ouest du Groenland (à gauche) et le promontoire du Judge Daly (à droite). Les flèches pointe vers la terrasse de 40 m qui constituait selon toute vraisemblance le seuil des lacs n°ˢ 1 et 2 au cours de l'émersion.

TABLE I

Radiocarbon dates quoted in this study

Lab number	Location	Age (Years BP)	Stratigraphy	Relative related sea level (m asl)
G.S.C.-3041	Beaufort Lakes[1]	8050 ± 120	Raised marine silt	116
S-1990	Beaufort Lakes[1]	8200 ± 215	Raised marine silt	116
AA-656	Beaufort Lakes	7060 ± 670	Glaciomarine silt from piston core, Lake 3	> 40
TO-205	Beaufort Lakes	5880 ± 70	Glaciomarine silt from piston core, Lake 3	≥ 40
TO-206	Beaufort Lakes	3750 ± 60	Glaciomarine silt from piston core, Lake 1	13-18

[1] These dates were previously quoted in England (1983). The dates were conventional radiocarbon dates on collections of mollusc shells. The remaining three dates were analyses of single molluscs run at the University of Arizona and University of Toronto tandem accelerator laboratories.

The lakes progressively emerged from the sea during regional deglaciation which began around 8000 BP (Table I) (ENGLAND, 1983). An erosional threshold cut in bedrock at *ca.* 40 m a.s.l. around Lakes 2 and 3 (Fig. 3) indicates that the upper two lakes emerged as one basin. A bedrock sill at approximately 18 m served as the probable threshold which isolated Lake 1, although several other lower elevation terraces (14 to 18 m) may have served as the original sill. By dating *in situ* molluscs at, or close to, the marine to lacustrine transition in Lakes 3 and 1, it is estimated that emergence of the two basins occurred at *ca.* 5800 to 5600 BP, and *ca.* 3500 BP, respectively (RETELLE *et al.*, in review).

At present, the lake waters are not chemically or thermally stratified as are some coastal lakes on northern Ellesmere Island (HATTERSLEY-SMITH *et al.*, 1970; JEFFRIES *et al.*, 1983). The three Beaufort Lakes contain freshwater from the surface to the base (Fig. 4).

At Beaufort Lakes in 1981 and 1982, the two major streams in the basin began to flow into Lake 2 in early to mid-June, with peak discharge reached in late June. Snowmelt decreased through early July and essentially terminated in August as snow rapidly melted from the basin. During the height of melt season (late June) suspended sediment concentrations in the inlet streams measured between 0.06 and 0.12 g/l. These values are several orders of magnitude lower than streams from proglacial environment (GUSTAVSON, 1975; OSTREM, 1975; GILBERT, 1982).

STRATIGRAPHY OF LACUSTRINE AND MARINE SEDIMENT CORES

Sediment cores ranging from 1 to 4.8 m in length were recovered from the three lakes. Representative cores from the lakes are shown in Figure 5. In each lake, laminated to massive lacustrine silt overlies sandy to pebbly fossiliferous glaciomarine silt. The two units are separated by a distinctive black sulfidic transition zone that represents an interval of basin isolation during isostatic emergence.

The length of core recovered from each basin was limited by the ability of the corer to penetrate the coarse glaciomarine unit. Additionally, friction against the core barrel wall impeded penetration through stiff inorganic sediments at depth. Because of the higher sedimentation rate in Lake 2, over 4 m of lacustrine sediments have accumulated since basin emergence while only 2 m of sediment were deposited in Lake 3 over the same period. Thus, a longer marine sediment record was cored
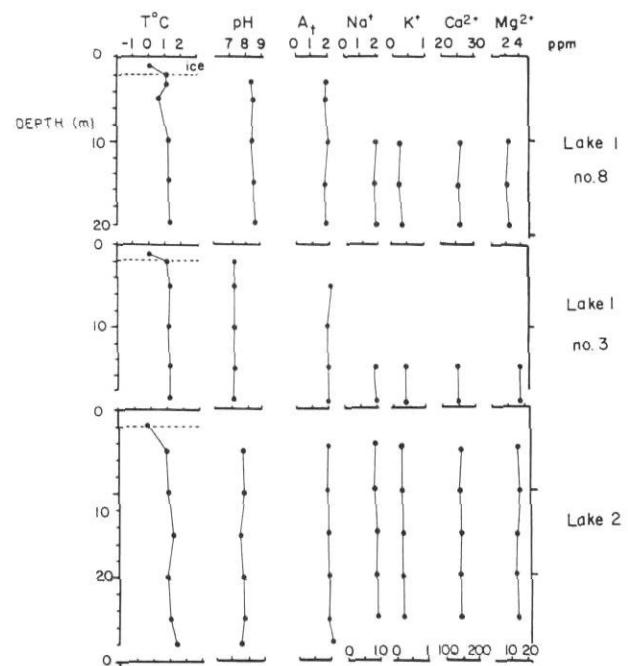

FIGURE 4. Temperature and chemistry of lake and stream waters, June 1981. A = total alkalinity; note change in scale for lake 3 diagram.

Températures et composition chimique des eaux lacustres et courantes, juin 1981. A = alcalinité totale. À noter le changement d'échelle du diagramme du lac n° 3.
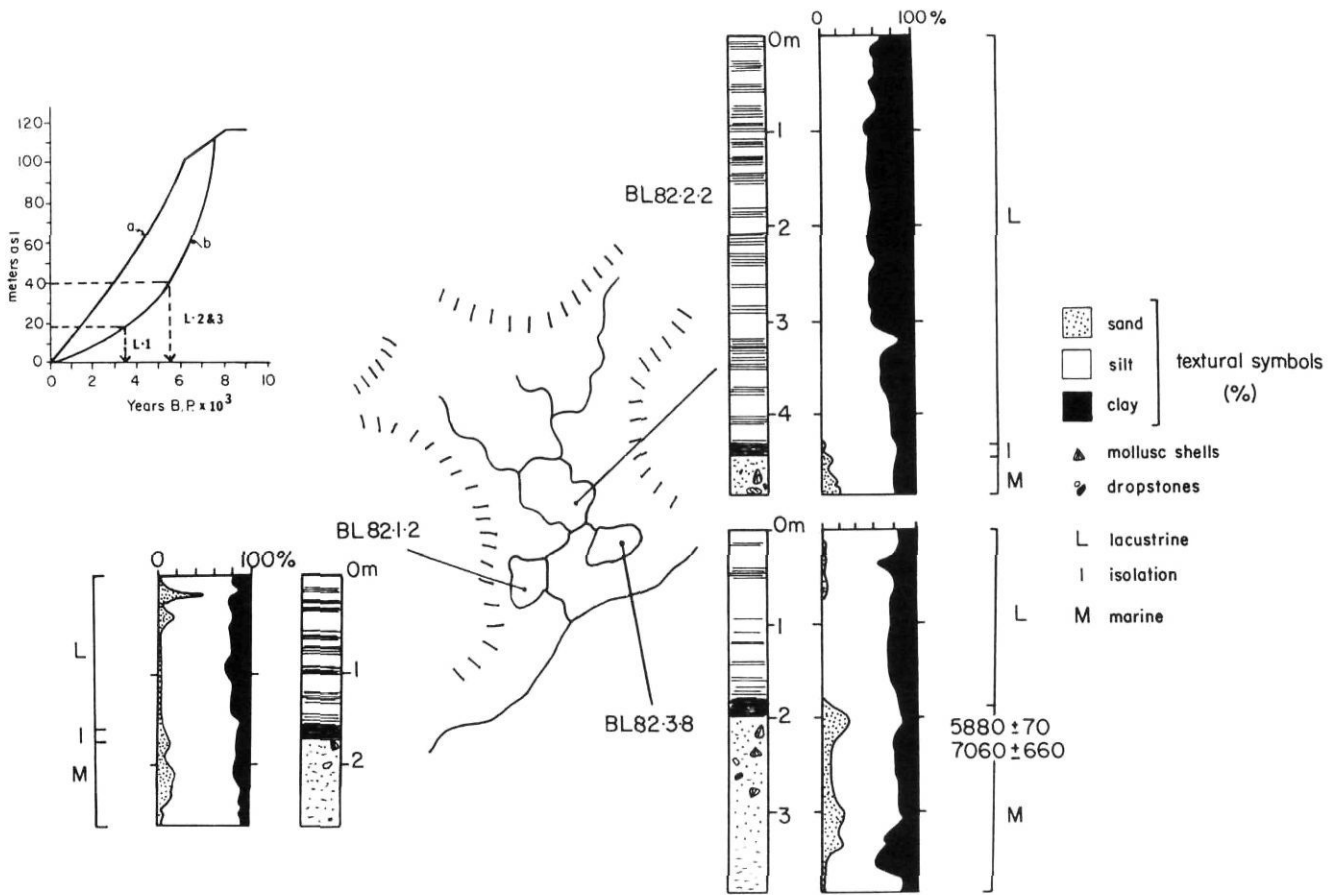
FIGURE 5.   Stratigraphy and grain size of representative cores. Inserted diagram in upper left designates proposed emergence chronology for the lakes. Curve "a" is from ENGLAND (1983); curve "b" from RETELLE *et al.* (in prep.).

Stratigraphie et granulométrie de carottes représentatives des trois lacs. Le diagramme en haut à gauche présente le déroulement chronologique probable de l'émersion. La courbe "a" est de EN-GLAND (1983); la courbe "b" est de RETELLE et al. (en prép.).

from Lake 3 (Core 3-8, Fig. 5) while a long and higher resolution lacustrine section was cored from Lake 2.

GLACIOMARINE SEDIMENTS

Glaciomarine sediments in the cores are olive-gray, sandy to clayey silt that contains dropstones and marine invertebrate macro- and microfauna. Bedding is absent to faint due to bioturbation (Fig. 6). Black sulfidic mottling and crinkled laminations are present, although these are mainly found around mollusc shells.

Marine sediments recovered in sediment cores consist of two distinct facies (Fig. 5). From approximately 205 cm to 335 cm depth, in core 3-8 the sediments are coarse-grained sandy silt with dropstones and abundant macrofaunal remains. Sand contents (> 62 μm) range between 10 to 30 % (by weight) over this interval. Dropstones suspended in the sandy mud matrix are pebble to gravel size. Paired valves of *Portlandia arctica* retaining the periostracum, were found in several locations in this coarse facies. The microfauna, is dominated by the high arctic inner shelf foram *Islandiella hellenae*, indicative of normal marine salinities (Vilks, pers. comm., 1983).

The core section from 335 to 390 cm is finer-grained with lower sand content (range = 2 to 5 %) and few dropstones. No macrofaunal remains were located in this core interval. With the exception of a crinkled black lamination overlain by a small gravel pod at 370 cm, this section is massive and featureless clayey silt. In contrast to the upper section of marine sediments, ice-rafted material is negligible.

Marine sediments from Lake 1 (core 1-2; Fig. 5) display a decreasing trend in coarse material from 20 % sand at 215 cm to approximately 5 % sand at 170 cm in the black sulfidic laminated zone. This gradual change from coarser- to finer-grained sediments through the marine to lacustrine transition is paralleled by a microfaunal change from full marine to estuarine (G. Vilks, pers. comm., 1984). Paired valves of *Portlandia arctica*, a species tolerant of low salinity, were found at 185 cm, just below the marine to lacustrine contact.

TRANSITION ZONE SEDIMENTS

Separating the glaciomarine sediments from the overlying lacustrine sediments is a distinct transition zone of massive to microlaminated black sulfidic clayey silt (Fig. 7). Alternating
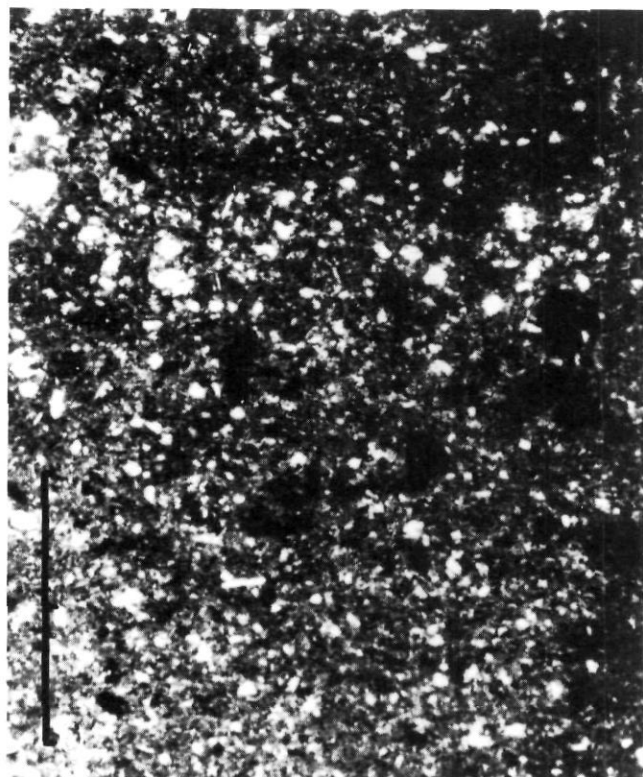
FIGURE 6.   Photomicrograph of sandy glaciomarine sediments from Lake 3. Black vertical bar scale equals 1 mm.

Microphotographie de sédiments glaciomarins sablonneux provenant du lac n° 3. L'échelle verticale représente 1 mm.
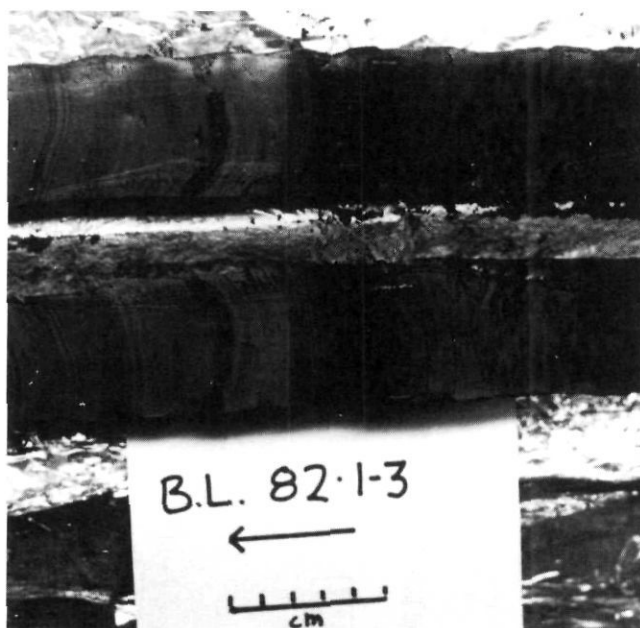

FIGURE 7.   Photograph of core 82-1-3 showing well-laminated to massive lacustrine sediments (left) and mottled to diffusely bedded glaciomarine sediments (right) separated by black microlaminated to massive sulfidic silt.

Photographie de la carotte n° 82-1-3 qui montre des sédiments lacustres d'aspect laminaire à massif (à gauche) et des sédiments glaciomarins d'aspect tacheté à légèrement stratifié (à droite) séparés par du limon noir sulfuré d'aspect microlaminaire à massif.

black and gray laminae, averaging 0.5 to 1.0 mm thick, grade upward from more massive black silt to laminated or massive-bedded lacustrine sediments. With prolonged exposure to air the black sulfidic layers oxidize to reddish-orange color. The sulfidic staining is commonly associated with fecal pellets that lie sub-parallel to lamination (Fig. 8). Intervening light-colored laminations are not graded and consist of silt to fine sand-size detrital grains.

LACUSTRINE SEDIMENTS

The upper sediment unit in the cores is a grayish-olive laminated clayey silt that ranges in thickness from 1 to 4.3 m (Fig. 5). In the three lakes, average grain size distribution is between 20 to 30 % clay, 70 to 80 % silt, and generally less than 1 % sand, although several mudflow layers contain as much as 50 % material coarser than 62 μm.

Sediment analyses from a Lake 2 core are shown in Figure 9. Mean grain size for the Lake 2 section increases upward from 2.5 to approximately 3.5 μm. Organic carbon and loss-on-ignition analyses demonstrate the paucity of organic material in the basin (less than 1 % carbon); slight upward increasing trends probably indicate increasing vegetation in the catchment since emergence.

Primary sedimentary structures include massive beds up to 10 cm thick and graded and multiple-graded discrete lam-

inations. A majority of discrete laminations consist of a couplet that probably represents one year of sediment deposition (Fig. 10). The base of the lamination is fine sand to coarse silt that may or may not show upward fining. The contact with the underlying lamination commonly shows evidence of loading in the form of miniature ball and pillow structures. Fine silt and clay particle agglomerates, resembling egg-shaped fecal pellets (cf. SMITH and SYVITSKI, 1982) or tabular intraclasts, are found in the upper half of the basal portion of the lamination. The basal portion of the couplet is probably introduced into the lake during late spring to early summer runoff.

The upper part of the lamination couplet is a dark, fine-grained silty clay that contains disseminated organic detritus. Sand grains, as coarse or coarser than those in the base of the lamination are found in thin diffuse layers or suspended in the silty clay (Figs. 10-11). Presumably, the upper portion of the couplet accumulates from the settling of fine sediment in the lake for the remainder of the year following runoff. Coarse material suspended in the upper part of the lamination may be from several sources. The grains may be of eolian origin, dropped into the lake after melting of the ice cover or blown in from unvegetated delta, outwash, or beach sources during the late summer ice-free period. Alternatively, the coarse grains may be attributed to a "slush-out" origin (KNIGHT, 1971), carried onto the ice surface by slushy debris flows from inlet stream valleys.
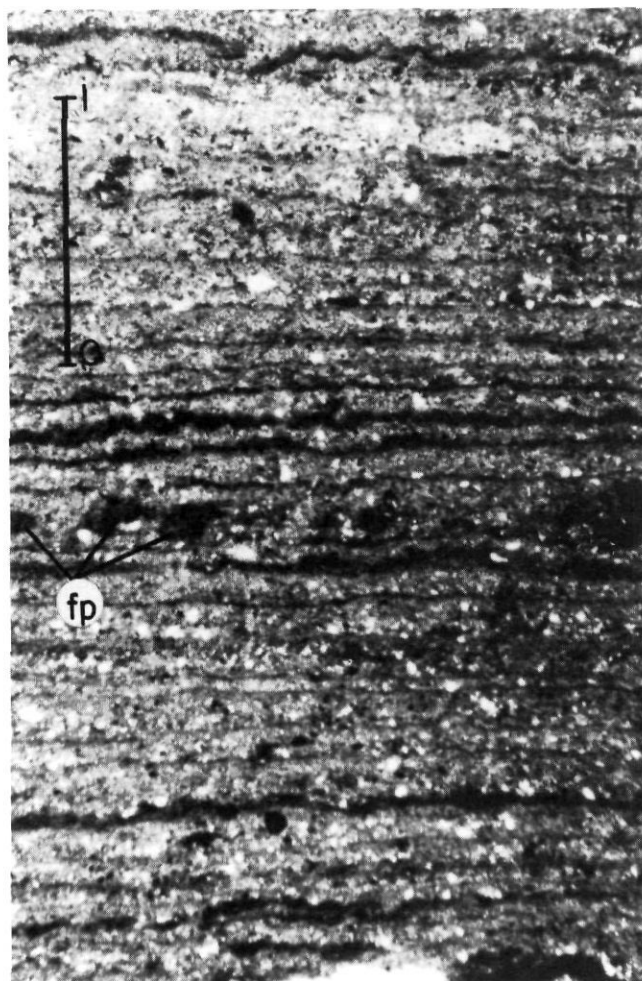
FIGURE 8. Photomicrograph of isolation zone sediments from Lake 3. Vertical bar scale equals 1 mm. Fecal pellets designated fp.

Microphotographie des sédiments de la zone de transition du lac n° 3. L'échelle verticale représente 1 mm. Les coprolithes sont identifiés par les lettres fp.

More complex laminations include multiple-graded beds (Fig. 11) that may represent both meltwater pulses or turbidites generated by slope failure within one season.

Series of well-defined laminae are separated by beds of massive, diffusely laminated fine sediments with coarse sand grains dispersed throughout. Lake 3, which has the lowest sedimentation rate (average 0.35 mm/yr) is dominated by massive sediments separated by very thin to diffuse laminations. In contrast, Lakes 2 and 1, with higher sediment influx (0.75 and 0.60 mm/yr, respectively) contain thicker sets of discrete laminae separated by diffuse layers. Figure 12 shows lamination thickness from cores in Lakes 2 and 1. In Lake 2, 411 individual laminations were deposited in approximately 5800 years since basin isolation, while in Lake 1, only 275 laminae were deposited in the 3500 years since emergence. In Lake 2, laminations are thickest at the bases of the lacustrine section although thick beds (up to 60 mm) occur up to the surface. The dominance of the thick, massive,

fine-grained sediments represents low sediment influx into the distal basin of Lake 2. Mean grain size (Fig. 9) is also finer in the basal part of the section. The upper section of the Lake 2 core (2100 mm to the surface) and the Lake 1 core (Fig. 12) are predominantly comprised of thin bedded laminations and graded beds. In both cores, however, the upper 100 to 200 mm is diffusely bedded indicating low rates of deposition over the upper part of the sediment record.

DISCUSSION

Sediments contained in the Beaufort Lakes basin represent a period of glaciomarine sedimentation followed by progressive basin isolation and subsequent lacustrine deposition. Ultimately, the facies distribution is glacioisostatically controlled. In the following sections, the interpretation of the various facies is discussed and referenced to a provisional chronology constructed with the aid of radiocarbon dates from shells in raised marine and core sediments. Environmental changes seen in the core record can then be compared to the chronology of marine and glacial events reported from the land-based record.

GLACIOMARINE SEDIMENTS

Glaciomarine sediment accumulated in each basin while it was isostatically depressed below sea level. Prior to initial isostatic emergence (8200 to 8000 BP) the sea stood at the marine limit in the Beaufort Lakes basin (116 m). Beaches at this elevation in the basin and in other nearby inlets are poorly developed; marine sediments of this age often contain a sparse fauna in comparison to younger lower elevation deposits. ENGLAND (1983) attributes the restricted shoreline development and the "barren silts" to pervasive landfast sea ice or ice shelves that may have blocked inlets during the glacial maximum. In contrast, younger raised marine deposits contain a richer and diverse fauna, while beach development and deltaic deposition is more favorable due to ice-free conditions and the increased availability of meltwater during the early to middle Holocene (ENGLAND, 1983; RETELLE, in press).

Textural and faunal evidence from glaciomarine sediments in the Beaufort Lakes cores may support the paleoclimatic interpretation of the land-based glacial and marine record. The coarse and fine-grained glaciomarine facies seen in the cores are texturally similar to ice-rafted and ice-distal sediments that have been described from Frobisher Bay on eastern Baffin Island (OSTERMAN and ANDREWS, 1983). Marine depositional processes in the Beaufort Lakes embayment are somewhat different however, from the tidewater glacier environment of Baffin Island fiords. As in fiords, sediment sources include fluvial input from snowmelt, ice-rafted material from local landfast sea ice, pack ice or icebergs, and mass flow and eolian sediment. In an emerging coastal lake basin, however, a higher percentage of sediment is probably contributed by former shore-fast ice rafts that drift basinward after freezing beach sediments to basal layers (REIMNITZ et al., 1978; BARNES et al., 1982; TAYLOR and McCANN, 1983). During periods of severe climate, multi-year fast ice can seal off
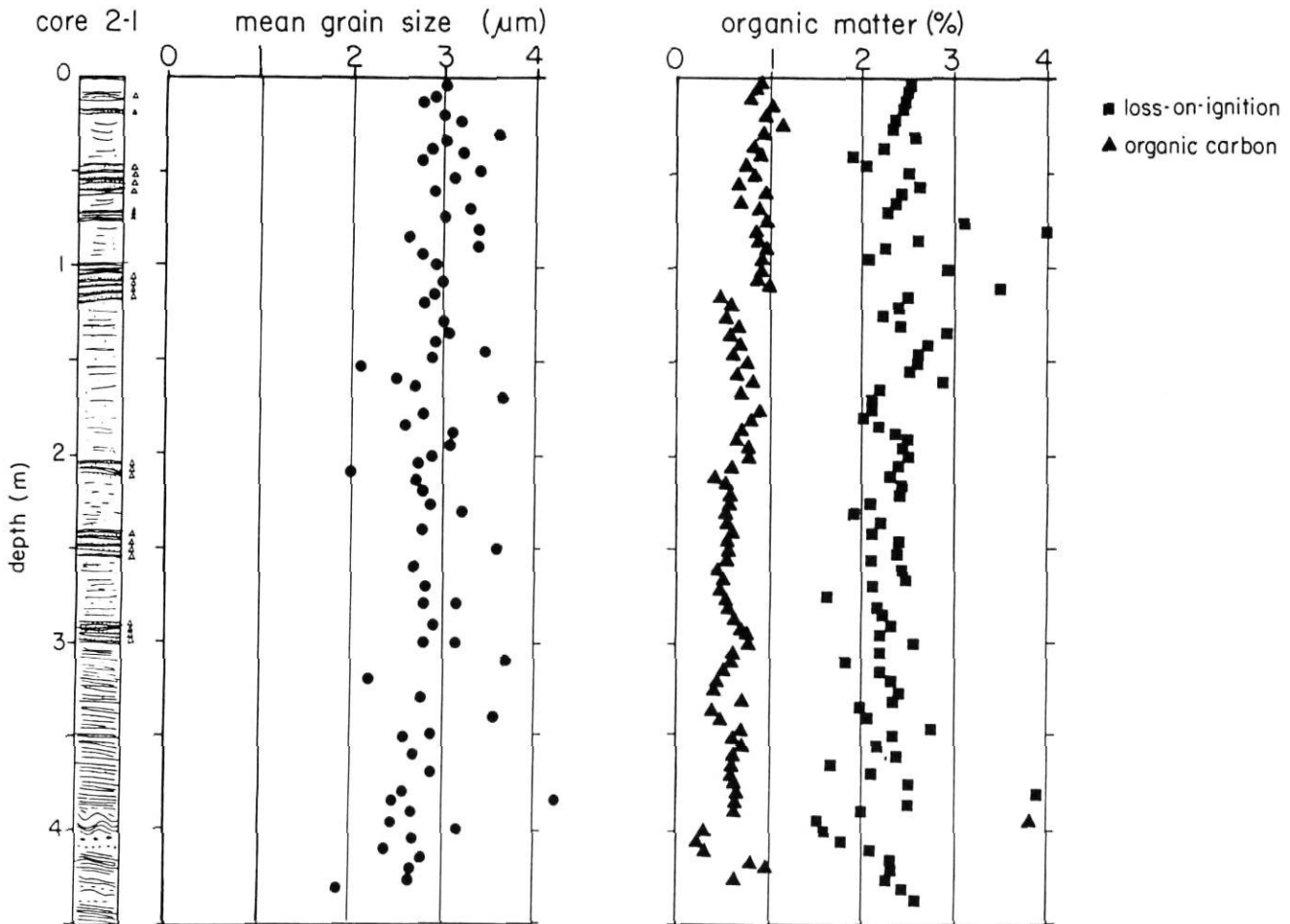
FIGURE 9. Stratigraphy and sediment analysis from core 82-2-1, Lake 2. Graded beds in stratigraphic column designated by small triangles.

Stratigraphie et analyse sédimentologique de la carotte n° 82-2-1 du lac n° 2. Les petits triangles dans la colonne de la stratigraphie identifient les lits granoclassés.

embayments, prohibiting berg and pack ice penetration, thus reducing erosional and depositional capabilities of fast ice during breakup. This is a particularly important phenomenon in the northern Queen Elizabeth Island where today, multiyear sea ice makes up to 70 % of the ice in the inter-island channels (TAYLOR and McCANN, 1983).

Fine-grained sediments from the base of core 3-8 demonstrate a period when ice rafting and fluvial input decreased due to the climatic severity during the glacial maximum. No macrofossils were found below the 3 m level in this core, further suggesting that conditions were unfavorable for fauna in deeper portions of the embayment (*ca.* 100 m depth), although the presence of *Hiatella artica* and *Portlandia arctica* near the shoreline of the embayment may indicate an open shallow lead where a marginal community could live.

The warming of climate and subsequent breakup of sea ice during the early to middle Holocene in the inlets can be demonstrated by the increased sand contents in the upper portion of the Lake 3 cores. This is presumably due to increased runoff and ice rafting. In addition, macro-fossils are relatively abundant in the cores, with the occurrence of *Portlandia arctica*

and *Astarte borealis*. This evidence concurs with other climate proxy data such as the record of driftwood accumulation (STEWART and ENGLAND, 1983), pollen stratigraphy (ANDREWS, 1982), macrofaunal range extensions (ANDREWS, 1972; STEWART and ENGLAND, 1983) and the oxygen isotope record from ice cores (DANSGAARD *et al.*, 1970; PATERSON *et al.*, 1977; FISHER and KOERNER, 1980), all of which suggest a middle Holocene Climatic Optimum at *ca.* 5000 BP.

Textural evidence from the Lake 1 marine sediments demonstrates a period of moderately coarse sediment influx prior to the lake emergence at around 3500 BP (Fig. 5) and a gradual transition from coarse to fine sedimentation through the isolation contact. The decrease in coarse sediment during emergence may indicate the formation of landfast sea ice which sealed off the basin during late Holocene cooling. This event was most likely synchronous with the formation of the larger scale ice shelves on the north coast of Ellesmere Island. On the basis of the youngest radiocarbon dated driftwood behind the Ward Hunt Ice Shelf, CRARY (1960) estimates that the initial formation of the ice shelf and closure of Disraeli
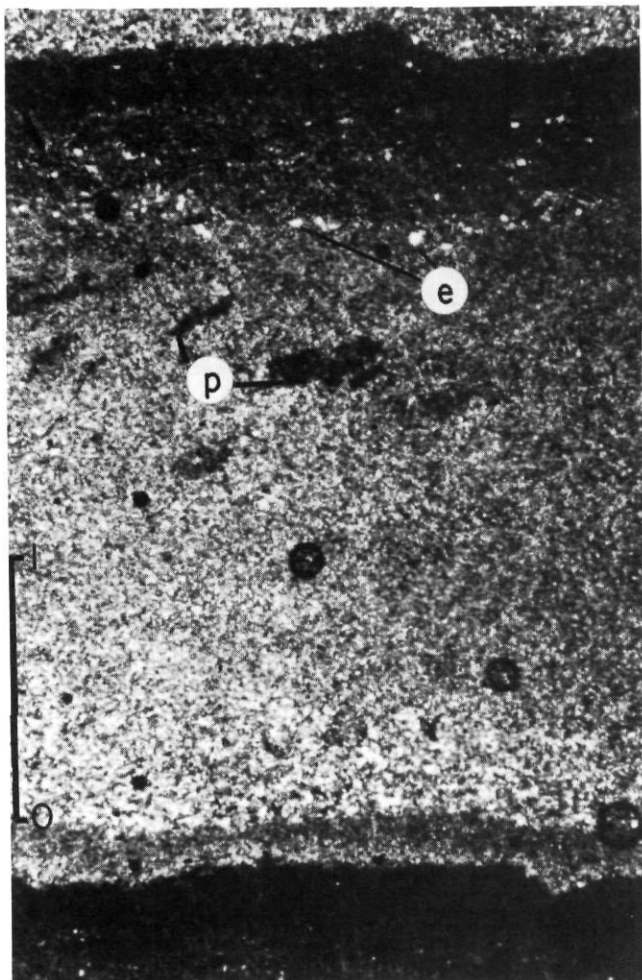
FIGURE 10. Photomicrograph of graded lacustrine lamination, core 82-2-1, Lake 2. Vertical scale equals 1 mm. Intraclasts and fecal pellets = p; eolian grains = e.

Microphotographie d'une lamine lacustre granoclassée, carotte 82-2-1 du lac n° 2. L'échelle verticale représente 1 mm. Les intraclastes et les coprolithes = p; grain éolien = e.
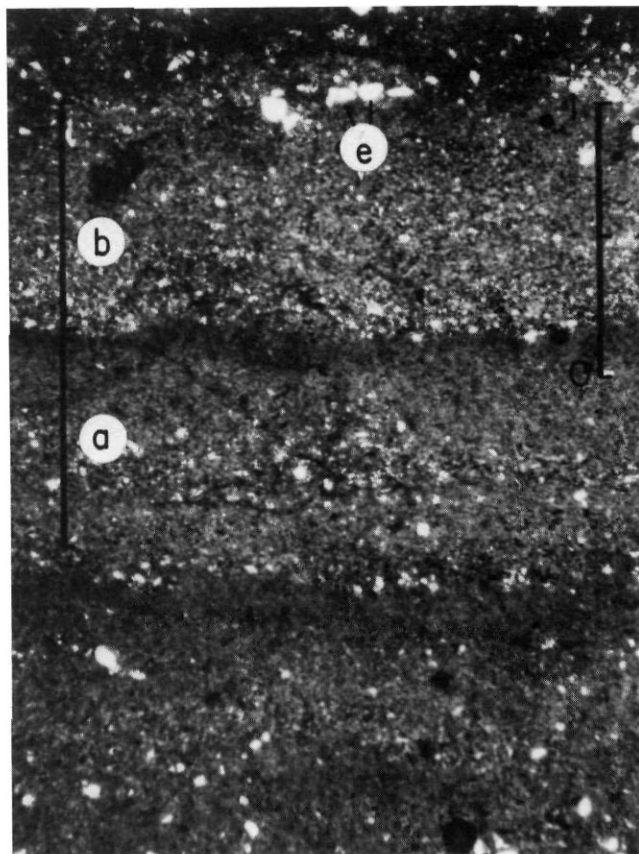

FIGURE 11. Photomicrograph of graded lacustrine laminations, core 82-1-3. Lower lamination (a) shows evidence of multiple grading. Upper lamination (b) has diffuse cross-laminations at base and coarse sand grains (e) at top. Vertical scale is 1 mm.

Microphotographie de laminites lacustres granoclassées, carotte n° 82-1-3. La lamine inférieure (a) montre un granoclassement multiple. La lamine supérieure (b) laisse voir des stratifications obliques peu nettes à la base et des grains de sable grossier (e) vers le haut. L'échelle verticale représente 1 mm.

Fiord occurred at around 3000 BP, although LYONS and MIELKE (1973) indicate that initial formation was underway by at least 3700 BP. Likewise, driftwood exclusion from Clements Markham Inlet, also on the north coast of Ellesmere Island, began at ca. 4200 BP (STEWART and ENGLAND, 1983). Pollen evidence from Baffin Island suggests that late Holocene cooling began around 3600 BP (ANDREWS et al., 1982). Hence, the trends of decreasing coarse sediment input in the Lake 1 basin prior to emergence at around 3500 BP probably reflect the same cooling trends seen in other climate proxy records for the period prior to 3000 BP.

MARINE TO LACUSTRINE TRANSITION

The gray to black microlaminated zone between the marine and lacustrine sediments represents the emergence and isolation of the lake basin from the sea with bottom waters of normal marine salinity trapped at the base of the lake. Saline waters became stagnant and poor in oxygen and remained in the lake bottoms until mixed with freshwater from runoff. Density-stratified arctic lakes on the north coast of Ellesmere Island contain this distinctive laminated black sulfidic mud at the sediment/water interface and also at the lacustrine/marine sediment contact in the sediment cores (Retelle, work in progress).

Transition zones of this type have been described in similar marine-lacustrine sedimentary sequences in Sweden (ERICSON, 1973) and Spitsbergen (HYVARINEN, 1970). Fine-grained black sulfidic clayey silt layers have also been documented in cores from fiords in Alaska (HOSKIN and BURRELL, 1973) and Baffin Island (Jennings, pers. comm., 1985) and in cores from the Black Sea (BERNER, 1970a). The black coloration is attributed to the presence of the iron monosulfides, mackinawite (Fe_xS_{1+x}) and greigite (Fe_3S_4). these unstable sulfide phases are precursors to pyrite ($Fe S_2$) that normally colors the sediment gray. The black precursor minerals usually form as a result of attenuated sulfate reduction and limited
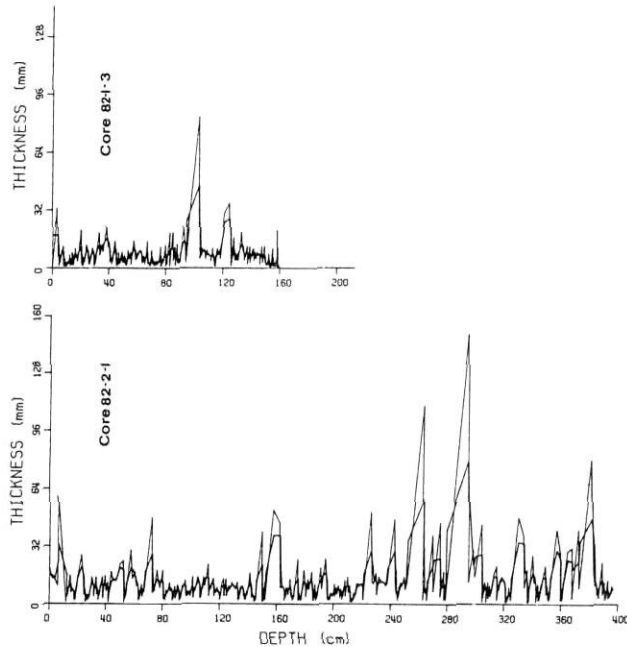
FIGURE 12.   Diagram of lamination thickness in cores from lakes 1 and 2. Dark line is a three point running mean of individual data points, using a 1-2-1 weighting.

Diagramme de l'épaisseur des laminites dans les carottes du lac n⁰ˢ 1 et 2. La ligne noire représente la moyenne mobile de trois valeurs de chacune des données, selon une pondération de 1-2-1.

LACUSTRINE SEDIMENTS

Lacustrine sediments in the Beaufort Lakes basin consist of alternating massive to diffuse beds and discrete laminations deposited since emergence of each basin from the sea. Due to the low sediment concentration of inflowing streams and the presence of denser sea water in the basin, at least for a period of time after emergence, it is likely that most of the sediment was deposited by overflow and interflow processes. Occasional turbidite deposition resulted from prodelta slope failure. Sequences of laminations (or varves) in the cores most likely occur during periods of relatively increased sediment influx while massive to diffuse beds represent longer periods of slow sedimentation.

Sequences of alternating massive and laminated lake sediments have been studied in cores from lakes on Baffin Island (D. Lemmen, R. Gilbert, personal communications, 1985). Distinct laminated horizons that could be correlated across the lake probably represent ice-free conditions when sediment could be dispersed by wind currents blowing across the lake surface. Massive sediments represent colder periods when meltwater influx was lower and ice cover on the lake was more permanent and winds could not distribute sediments.

In contrast to the Baffin Island sediments, the diffuse sediments at the base of the Lake 2 core probably do not relate to a prolonged period of climatic severity. Other middle Holocene climate proxy evidence from the high arctic, cited previously, demonstrate that the Holocene Climatic Optimum was reached by around 5000 BP. It also has been demonstrated that cooling began after the middle Holocene warm period, sometime prior to 3000 BP (STEWART and ENGLAND, 1983). Thus, in terms of texture and structure, the Beaufort Lakes sediments seem to indicate a reversed situation if the model proposed for Baffin Island lakes is applied.

The lamination distribution in Lake 2 is apparently not a function of density stratification. Lakes on northern Ellesmere Island (Lakes A and B, Fig. 1) retaining sea water (30 ‰) beneath a sharply defined halocline contain well-laminated lake sediments. Moreover, these lakes have emerged since the middle Holocene warm period and contain well-developed laminations despite the presence of multi-year ice cover on the surface (research in progress).

The most likely interpretation for the Lake 2 sequence is that the sediment record reflects a combination of delta progradation into the distal part of the Lake 2 basin and the effects of changing climate. The reason why the sediments at the base of the lacustrine sequence do not record changes in runoff is that the distal basin was probably starved of sediment. After the basin began to receive more proximal sediments, alternation of discrete laminations and massive beds recorded changes in snowmelt runoff regime. It is also a possibility that if open ice conditions existed on the lake during the middle Holocene, winds blowing across the lake surface from the mouth of the embayment towards the west would have inhibited rather than enhanced sediment plume dispersal, in the case of katabatic winds driving sediment from the sandur source. Periods of low sediment accumulation, seen in the

production of H₂S. Pyrite can form from monosulfides if there is sufficient organic material for metabolism and sulfate supply for sulfate-reducing bacteria. Sulfate is usually supplied by diffusion from the overlying water column. BERNER (1970a) cites evidence for black monosulfide occurrence in the Black Sea relating to periods of low sea level and increased freshwater influx. Fresh water entering the Black Sea contains only 0.35 umoles/l of dissolved sulfate in comparison to sea water which has about 28 umoles/l. In the Beaufort Lakes, black sediments would be deposited during basin emergence as sulfate became depleted from the bottom waters and not replaced after the basin became isolated. Although usually not the most limiting factors in monosulfide-pyrite transformation in normal marine conditions, the availability of elemental iron and sulfur is probably more important in euxinic and lacustrine environments (BERNER, 1970b, 1984).

The age of this transition was initially estimated by radiocarbon dates on organic matter from the sulfidic sediments however these dates proved to be too old (RETELLE, 1985; RETELLE *et al.*, in review). Better estimates were obtained by tandem acceleration dating of *in situ* mollusc shells located as close as possible to the transition. These dates yield a maximum age for basin isolation since emergence took place subsequent to marine sedimentation. At this time, it is not possible to stratigraphically detect the duration of density stratification in the lake basins. Ongoing research in several high arctic lakes containing sea water will hopefully shed light on this subject.

surface sediments may relate to climate deterioration during the last century.

CONCLUSIONS

Sedimentary sequences contained is coastal lacustrine basins on northern Ellesmere Island offer detailed information on the effect of glacio-isostatic uplift and climatic change on nearshore glaciomarine and lacustrine sedimentation.

Sediment cores were recovered from three lakes located below the Holocene marine limit along Robeson Channel. The lakes are now entirely freshwater and contain a sequence of nearshore glaciomarine sediments overlain by finely laminated lake sediments.

Glaciomarine sediments were deposited during isostatic depression of the coastal zone. The longest marine core section demonstrates two distinctive lithofacies. The base of the core (est. pre-8000 BP) is a fine silty clay with <2% sand. Macrofossils are rare in this section of the core. Coarse sediment deposition due to ice rafting and nival melt, as well as faunal occupation, was precluded due to the persistence of landfast sea ice or an ice shelf during the period of the glacial maximum. The upper marine facies includes a richer macrofauna and abundant coarse detrital grains (up to 26% sand), presumably due to the breakup of ice in the embayment and increased runoff during the middle mid-Holocene warm period.

Lacustrine sediments are well-laminated to massive and consist of clayey silt with minor amounts of sand. Although sediment accumulation rates are too low to have recorded detailed climatic changes since emergence, the lake sediment sequence demonstrates several important environmental changes. (1) The presence of alternating microlaminations of sulfide and fine clastic grains represents a period of basin isolation and trapping of sea water during emergence. (2) Grain size increase and changes in lamination thickness demonstrates the progradation of the delta into the distal basin of the lake. The more proximal record of the younger lake sediments shows a more highly resolved signal of the response of runoff and sedimentation to climatic change.

ACKNOWLEDGMENTS

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