Sedimentology of perennial ice-covered, meromictic Lake A, Ellesmere Island, at the northern extreme of Canada[1]

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Abstract: The sedimentology of coastal, meromictic Lake A, Ellesmere Island (83°00′N, 75°30′W), was investigated to understand the linkages between the extreme lake environment and its sedimentary features. Four facies were identified within the sedimentary record that represent stages of the lake's development from a marine embayment to a meromictic lake. Despite low ecosystem productivity, both clastic and biogenic materials contribute substantially, and highly seasonal sedimentation, pervasive ice cover, and anoxia in the saline bottom water (monimolimnion) act to preserve annual sedimentary units (varves) within the upper part of the sedimentary record. Sediment texture is predominantly silt and clay, but the irregular presence of sand indicates past episodes of higher energy stream discharge to the lake. Oxygen incursions into the chemocline likely cause bacteria mortality and provide elemental sulphur for iron sulphides that are deposited in the sediments. Millimetre-scale sedimentary pellets are also a conspicuous feature in the sediments and are interpreted to result from littoral sediment transport by ice-rafting. Many of Lake A's notable sedimentary features are also evident in other High Arctic meromictic lakes, particularly those on the northern coast of Ellesmere Island. These similarities and the important biogenic component identified in Lake A suggest that processes in these sedimentary environments are more complex than previously thought.

Résumé : La sédimentologie du lac méromictique A, sur l'île d'Ellesmere (83°00′N, 75°30′O), a été étudiée afin de comprendre les liens entre l'environnement extrême du lac et ses caractéristiques sédimentaires. Quatre faciès ont été identifiés dans les sédiments; ils représentent des étapes du développement du lac à partir d'un enfoncement marin à un lac méromictique. Malgré la faible productivité de l'écosystème, la matière clastique et biogénétique y contribue de manière importante et une sédimentation saisonnière élevée, un couvert de glace omniprésent et l'anoxie dans les eaux de fond salines (monimolimnion) préservent les unités de sédimentation annuelles (varves) dans la partie supérieure des sédiments. La texture du sédiment provient surtout du silt et de l'argile mais la présence irrégulière de sable indique d'anciens épisodes de décharge à grande énergie dans le lac. Des incursions d'oxygène dans le chemocline a probablement causé la mort des bactéries et a fourni du soufre élémentaire pour les sulfures de fer qui se sont déposés dans les sédiments. Des granules sédimentaires d'ordre millimétrique forment aussi une caractéristique remarquable bien visible; ils proviendraient de sédiments littoraux transportés par des banquises. De nombreuses caractéristiques du lac A sont aussi évidentes dans d'autres lacs méromictiques du Grand Nord, surtout ceux de la côte nord de l'île d'Ellesmere. Ces similitudes et la forte composante biogénétique identifiée dans le lac A suggèrent que les processus dans ces environnements sédimentaires soient plus complexes qu'à première vue.

[Traduit par la Rédaction]

Introduction

Permanently stratified (meromictic) lakes located in the polar regions are some of the most extreme lacustrine environments on Earth. Many high latitude meromictic lakes are coastal and formed primarily as a result of glacioisostatic rebound (e.g., Bradley et al. 1996; Gibson 1999). These former marine embayments contain trapped sea water and receive seasonal freshwater runoff from the surrounding landscape (Gallagher et al. 1989; Gibson 1999; Van Hove et al. 2006). Hence, these lakes are typically composed of a fresh, oxygenated upper unit (mixolimnion) overlying a saline, anoxic monimolimnion (Bradley et al. 1996; Gibson 1999).

In the monimolimnia, anoxia, strong reducing conditions, high concentrations of hydrogen sulphide, and, in some cases, hypersalinity limit the biota to bacteria that can withstand such harsh conditions (Parker et al. 1981; Doran et al. 2004). Cold water temperatures and permanent ice cover also contribute to the unusual limnology and biota within such lakes (Vincent et al. 2008*b*). Additionally, the most northerly Arctic lakes and many Antarctic lakes have peren-

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nial or near-perennial ice covers, which limit wave activity and interaction between the lake and the atmosphere for most of the year (Wharton et al. 1993). This situation, combined with strong stratification and highly seasonal sedimentation, creates an environment that promotes the formation and preservation of annually laminated (varved) sediments (Bradley et al. 1996). In the High Arctic, varve thickness and structure records are particularly useful as environmental proxies, since ice-core records provide the only other annual resolution paleoclimate records for studies of long-term variability (Bradley et al. 1996).

Despite the relative wealth of limnological information available from polar meromictic lakes, their sedimentary processes and deposits remain poorly documented, including only a few process studies (e.g., Davidge 1994; Retelle and Child 1996) and sedimentary investigations (Gilbert and Church 1983; Zolitschka 1996; Lewis et al. 2007). In some cases, studies have examined the sedimentary records of these lakes (e.g., Lamoureux and Bradley 1996), however, with an emphasis on sedimentary structures and physical properties.

This study reports a comprehensive analysis of the sedimentary record of meromictic Lake A at the northern extreme of the Canadian High Arctic. The objectives are to detail sedimentary features and related processes in the context of detailed ongoing limnological studies of the lake (Belzile et al. 2001; Van Hove et al. 2006) and to compare these features with those of other meromictic lakes in the region. This research also provides a baseline description of sedimentary characteristics for paleoenvironmental studies of Lake A and similar regional lakes.

Study site

Lake A (unofficial name (Hattersley-Smith et al. 1970); 83°00′N, 75°30′W) is located on the Marvin Peninsula in Quttinirpaaq National Park along the northern coast of Ellesmere Island, Nunavut (Fig. 1). The 4.9 km^2 lake is composed of a single, glacially overdeepened basin with a maximum known depth of 128 m. It has two major inlets from an unglacierized 36 km^2 catchment, including a stream that flows from smaller (0.9 km^2) meromictic Lake B (unofficial name (Hattersley-Smith et al. 1970)). A rock sill across the northern end of the lake isolates it from the Arctic Ocean. The only outlet flows into Rambow Bay, which is adjacent to the ~3000–5500 year old Ward Hunt Ice Shelf (Crary 1960; England et al. 2008). Catchment relief reaches >800 m above sea level (a.s.l.) and is underlain by the upper Ordovician M'Clintock Formation (pyroclastic and volcanic rocks with limestone inclusions (Okulitch 1991)). The mountains are mantled with felsenmeer, and evidence for past glacial erosion is pervasive across the landscape (Lemmen 1989).

The climate of northern Ellesmere Island is typical of High Arctic areas. Mean annual temperature at Alert, Nunavut (175 km east), is –18 °C and mean annual precipitation is 154 mm (Environment Canada 2008). Temperatures are above freezing only during July and August, and, at Alert, most precipitation falls during summer and autumn (July–October), mostly as snow. In this polar desert environment with continuous permafrost, herbaceous tundra vegetation is sparse and has limited species diversity (Edlund and Alt 1989).

Methods

Twenty one sediment cores were collected from Lake A in 2005 and 2006 with Aquatic Research Instruments gravity and percussion coring systems (Glew et al. 2001). Coring locations that were expected to contain the most detailed sedimentary records were chosen based on bathymetry, inlet and outlet locations, and previous research conducted at the lake. A transect of cores along a depth gradient was also collected to investigate the variability of sedimentation at different depths. The 2006 core sediment surfaces were sealed with sodium polyacrylate gel to prevent disturbance during transport (Tomkins et al. 2008).

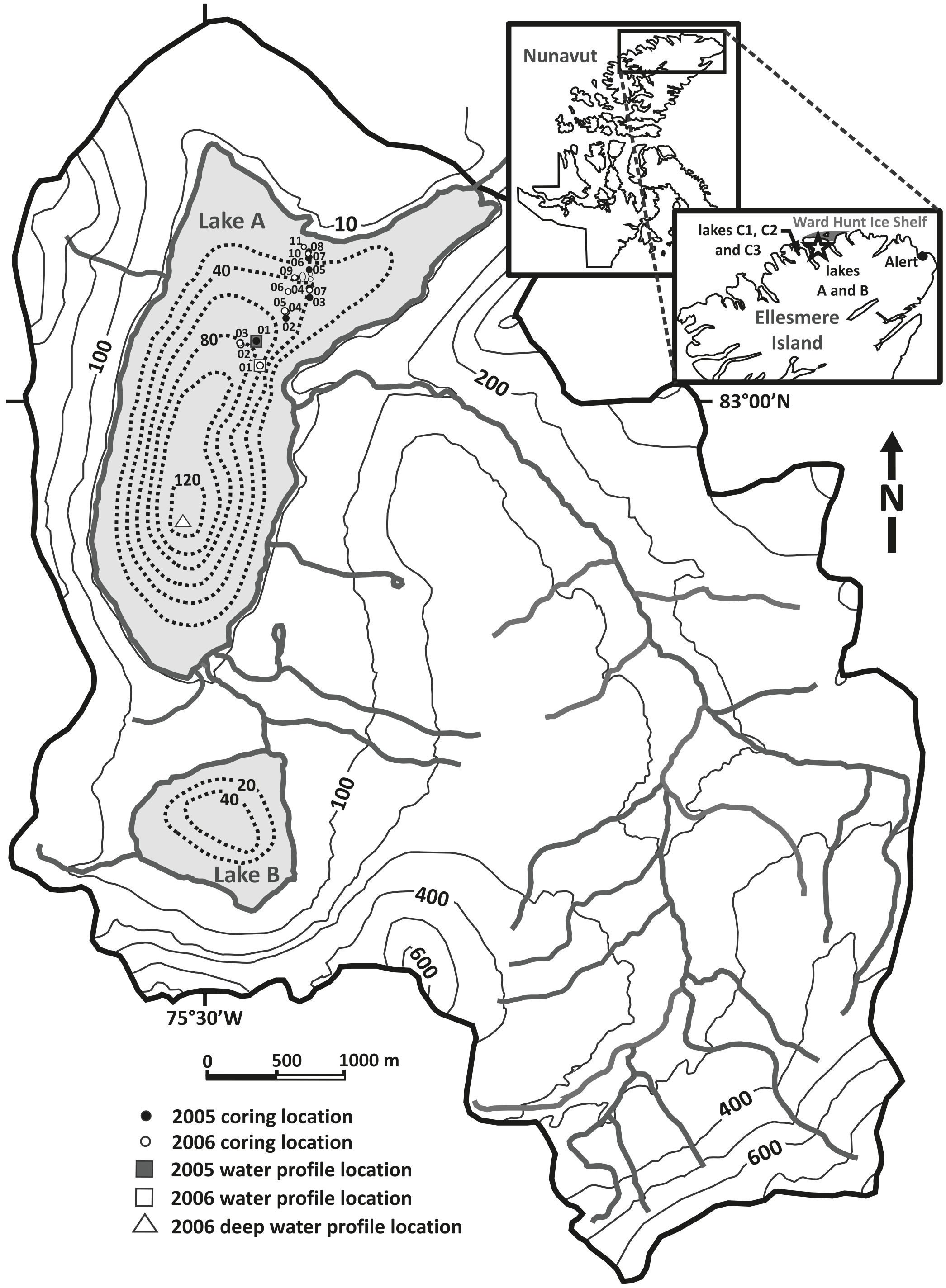
Water column properties were measured using a Hydrolab Surveyor 3 data logger (temperature, dissolved oxygen, pH, and conductivity) and a Richard Brancker Research (RBR) XR-420 CTD probe (salinity, temperature, and depth). The presence of dissolved hydrogen sulphide (H_2S) in the monimolimnion was evidenced by a distinct odour from water overlying all cores collected from below the oxycline.

In the laboratory, cores were split lengthwise, cleaned, photographed, and logged. Overlapping sediment slabs (7.0 cm × 1.5 cm × 0.3 cm) were sampled for thin section preparation following the methods of Lamoureux (1994, 2001). Thin sections were scanned at 2400 dpi, but detailed observations of microlaminae also required the use of light microscopy. Thickness measurements were obtained using a dissecting light microscope and a Quick-Chek QC-1000 measurement system mounted on an Acu-Rite Absolute Zero II precision measurement stage (±0.001 mm). Thin sections made for light microscopy observations from the sedimentary records of lakes A, B, C1, C2, and C3 (unofficial names (Hattersley-Smith et al. 1970); Fig. 1; Bradley et al. 1996; Lamoureux and Bradley 1996) were made available by Dr. Raymond Bradley.

Samples from core A-02-05 were weighed before and after oven drying overnight (60 °C) for measurements of density and water content to assess compaction. Radioisotopic dating was conducted on a representative core (A-02-05). Contiguous 3 cm^3 samples at 0.5 cm depth intervals from 0–3 cm were collected for ^{137}Cs determinations. After oven drying at 60 °C, gamma activity was measured for 80 000 s with an ORTEC high-resolution gamma counting system. ^{210}Pb activity was measured in 0.5 cm^3 samples collected at progressively larger depth intervals to 8.5 cm. The samples were oven-dried (60 °C), crushed, and analyzed with alpha spectroscopy (MyCore Scientific, Deep River, Ontario). Dates were established using the constant rate of supply ^{210}Pb dating model (Appleby and Oldfield 1978). As the sedimentary records did not contain macro organic material, bulk sediment was also collected at five locations within core A-04-06 for radiocarbon dating. These samples were dried for 24 h in an oven (60 °C) and submitted for accelerated mass spectrometry (AMS) radiocarbon dating at the KECK Carbon Cycle AMS Facility, Irvine, California (Table 1).

The core with the longest record (A-04-06) was sampled at 1 mm intervals for grain-size analysis. Samples were repeatedly treated with 40 °C 35% H_2O_2 for two to three

Fig. 1. Lake A bathymetry (in m), sampling locations, and catchment relief (m above sea level (a.s.l.); after Department of Energy, Mines and Resources Canada (1992*a*, 1992*b*). The study location relative to the Ward Hunt Ice Shelf, Agassiz Ice Cap, regional lakes, and meteorological records at Alert, Nunavut, is indicated with the inset maps. Bathymetric data were collected from point measurements through holes drilled through the ice cover in spring 1993, 2005, and 2006; and isobaths were interpolated between these locations.



weeks to remove organic material, followed by addition of 1–2 mL of sodium hexametaphosphate (38 g·L^{-1}) and sodium carbonate (8 g·L^{-1}). Samples were analyzed three successive times with a Beckman Coulter LS200 laser diffraction grain-size analyzer equipped with a fluid module under continuous sonication. The unaveraged third determination was retained for each sample.

Total organic carbon (TOC) and total nitrogen (TN) were measured at 0.5 cm increments within the upper 3 cm (to observe recent trends) and at 1 cm increments below 3 cm in cores A-02-05 and A-04-06. The samples were treated with dilute hydrochloric acid (2 N) for 24 h, freeze-dried, and crushed before measurement with a Leco CNS-2000 analyser. Soil standards and blank (no sediment) samples were

Table 1. Grain size data and total organic carbon (TOC), total nitrogen (TN), and C/N data for the four sedimentary facies of core A-04-06 and mean values for the entire A-04-06 core. Standard deviations are listed in parentheses.

	Grain size					TOC, TN, and C/N			
Facies	Sample size (n)	Mean (μm)	Clay (%)	Silt (%)	Sand (%)	Sample size (n)	Mean TOC (%)	Mean TN (%)	C/N (atomic)
4	179	6.8 (1.9)	21.2 (3.7)	78.1 (3.6)	0.7 (1.1)	21	1.9 (0.2)	0.2 (0.03)	15.4 (2.4)
3	86	8.1 (1.7)	18.8 (2.8)	80.9 (2.7)	0.3 (0.5)	9	1.9 (0.3)	0.1 (0.04)	16.4 (3.4)
2	197	5.6 (1.6)	26.5 (6.5)	73.5 (6.5)	0.0 (0.2)	19	2.3 (0.5)	0.2 (0.05)	18.1 (1.2)
1	65	5.3 (0.8)	27.5 (2.2)	71.5 (2.5)	1.1 (2.0)	8	1.0 (0.6)	0.1 (0.04)	21.1 (6.2)
Entire core	527	6.4 (1.9)	23.6 (5.7)	76.0 (5.7)	0.4 (1.0)	57	1.9 (0.6)	0.1 (0.05)	17.3 (3.5)

run to ensure proper instrument function during sample measurements and to establish error margins for the resulting data (±0.03%–0.10% carbon, ±0.04%–0.05% nitrogen).

A sample representative of the laminated sediments (1.9–2.4 cm) from core A-04-06 was analyzed with scanning electron microscopy (SEM) and energy dispersive X-ray spectrometer (EDS) analysis on JEOL JSM-840 Scanning Electron Microscopes. A sample of distinct ovoid features (26.4–26.5 cm) in core A-04-06 was analyzed in an Electroscan Environmental Scanning Electron Microscope (ESEM) 2020. Thin sections were also examined using an Applied Research Laboratories SEMQ Scanning Electron Microscope Quantometer with a TRACOR-Northern 5500 energy dispersive X-ray spectrometer.

Results

Limnology

The oxycline shows a rapid transition from surface waters that are supersaturated with oxygen to anoxic conditions at 13 m (Fig. 2). The transition between fresh and euxinic, saline water is evident through the chemocline at 10–30 m, and a narrow band of iron-rich water exists at ~30 m depth (Gibson et al. 2002; Van Hove et al. 2006). The thermocline is present between 15 and 30 m and the maximum water temperature is found between 15 and 17 m (8.4 °C in May 2005 and 2006). Below the temperature maxima, the monimolimnion is 4 °C and has a salinity of ~31‰ (Fig. 2).

Spring ice thickness has been reported to be ~2 m (e.g., Hattersley-Smith et al. 1970; Jeffries et al. 1984; Gibson et al. 2002; Van Hove et al. 2006). In spring 2005 and 2006, mean ice thickness was ~1.5 m (n = 8) and 1.3 m (n = 11), respectively. However, the snowpack on the lake in those years was ~60 and 50 cm thick, respectively, which may have insulated the ice cover during the winter. A moat typically forms in summer around the edge of the ice pan, and the lake ice broke up significantly in 2003 and 2006 and melted entirely in 2008 (D. Mueller and J. Veillette, personal communications, 2007 and 2008).

Sedimentary record structure and lithology

The sediment surface

Microbial mats have been observed on the lake bottom at <1 m water depth along the delta (A. Jungblut, personal communication, 2008) and 20 m depth, and dark organic material with pinnacle forms has been observed at 62 m (Fig. 3; D. Andersen, personal communication, 2007). The organic matter at depth and evident at the surface of many cores obtained from below the oxycline occurred as black flaky material, forming uneven surfaces. This surface material reacted with the core sealant (Tomkins et al. 2008) and, as such, thin section analysis of this material could not be performed. Core A-10-06, obtained from within the chemocline but below the oxycline, had a thin, bright green microbial mat on its surface. The only core obtained from an oxygenated location (core A-11-06) had no visible surface organic material.

Sedimentary facies

Four different facies were evident within the Lake A sedimentary record that could be correlated between all cores obtained from 36.5–53 m water depth (Fig. 4). Sediments from areas close to the delta and from >53 m water depth were coarser and commonly interbedded with thick-graded sandy lenses, some of which had erosive basal contacts. Sediment deformation was minimal although disturbances were observed in core A-03-06. An erosive event removed 1.5 cm of sediment from a section of this core but did not affect core A-02-06, collected five metres away. Moreover, core A-03-06 was disturbed at depth while adjacent core A-02-06 did not show any evidence of disturbance. Coring-induced disturbance is unlikely, given the presence of undisturbed sediments above and below the disturbed section.

In the northern portion of the lake at water depths <54 m, the sedimentary record was largely undisturbed, and the longest, uninterrupted record was preserved. The lowermost facies (facies 1) contained massive clay (Fig. 5). This sediment was denser than that of other facies and had a grey hue (Munsell 2.18Y 6/2). Sub-millimetre black granules were notable within the massive mud and small clasts (up to 1 cm diameter) were frequent, typically just below the transition to facies 2. This facies had the finest grain size and lowest organic carbon, and nitrogen content of the four facies (Table 2; Fig. 6) and small fossil foraminifera (cf. *Eponides tener* (Brady), Vilks 1969) were present.

Facies 2 was composed of sediments with diffuse laminated structure (fine brown units with wavy black, red, and green laminae (0.1–0.7 mm thick)) and detrital organic fragments. On the core face, this facies appeared to have slightly wavy laminae throughout but in thin section, the units were vague (Fig. 5). This facies had relatively high chlorophyll concentrations (D. Antoniades, unpublished data, 2007) compared with the other facies and a greenish brown hue (6.71YR 2/4). The sediment texture was finer than the overlying facies and contained the lowest proportion of sand (Table 1). Ovoid, pale yellow to red-hued amorphous features were present alone or in bands with connective dark

Fig. 2. Profiles of temperature, dissolved oxygen, conductivity, and pH in the Lake A water column below the ice cover on (*a*) 19 May 2005 and (*b*) 29 May 29 2006. Note that specific conductivity measurements of 10 000 μS·cm^{-1} indicate measurements above the upper limit of instrument sensitivity. Shading at the top of the profile indicates ice cover thickness.

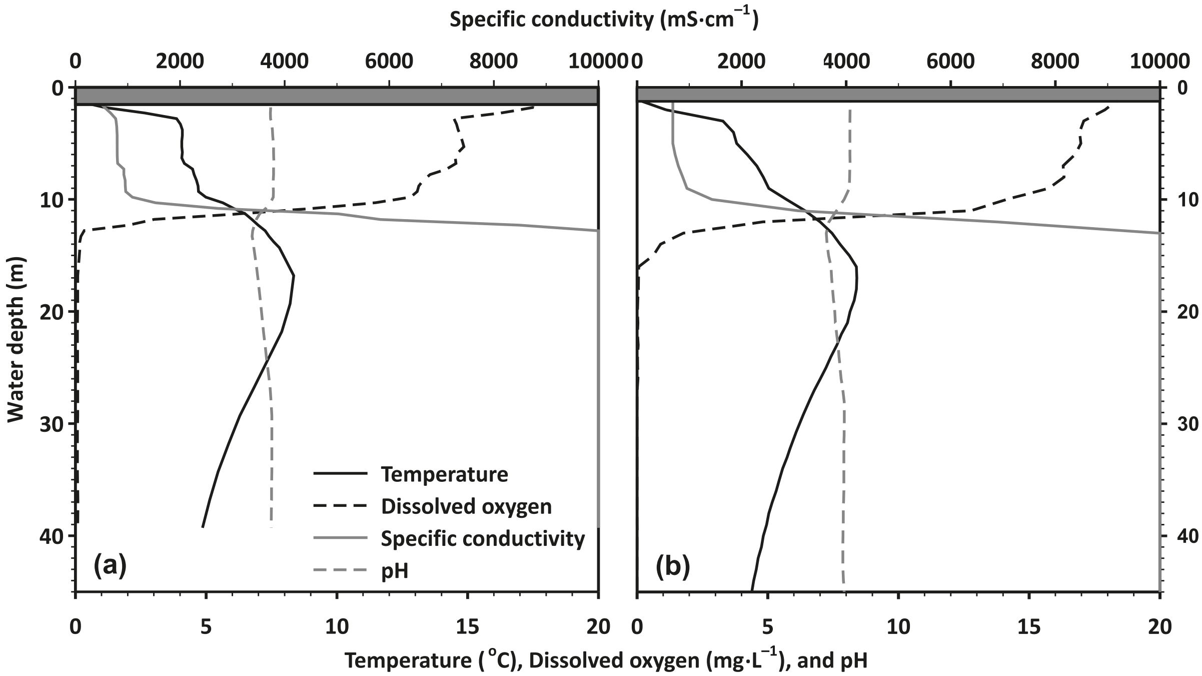
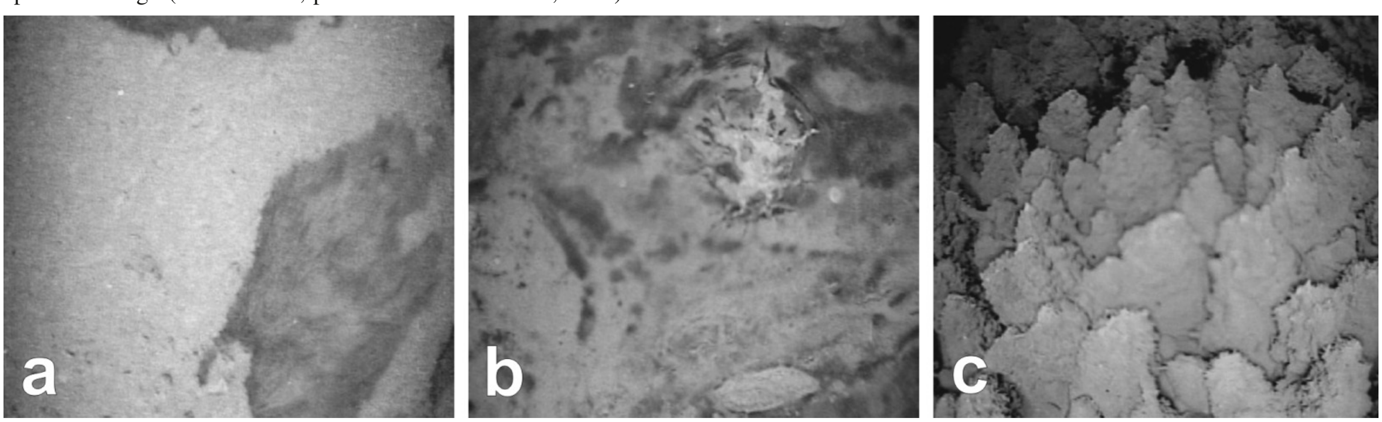


Fig. 3. Images of the bottom of Lake A at (*a*) 10 m, (*b*) 20 m and (*c*) 62 m water depth (reproduced with the permission of D. Andersen). The tuft of green plant material in (*a*) and the opening in the cyanobacterial mat in (*b*) are each ~10 cm wide and the pinnacles in (*c*) are up to 5 cm high (D. Andersen, personal communication, 2007).

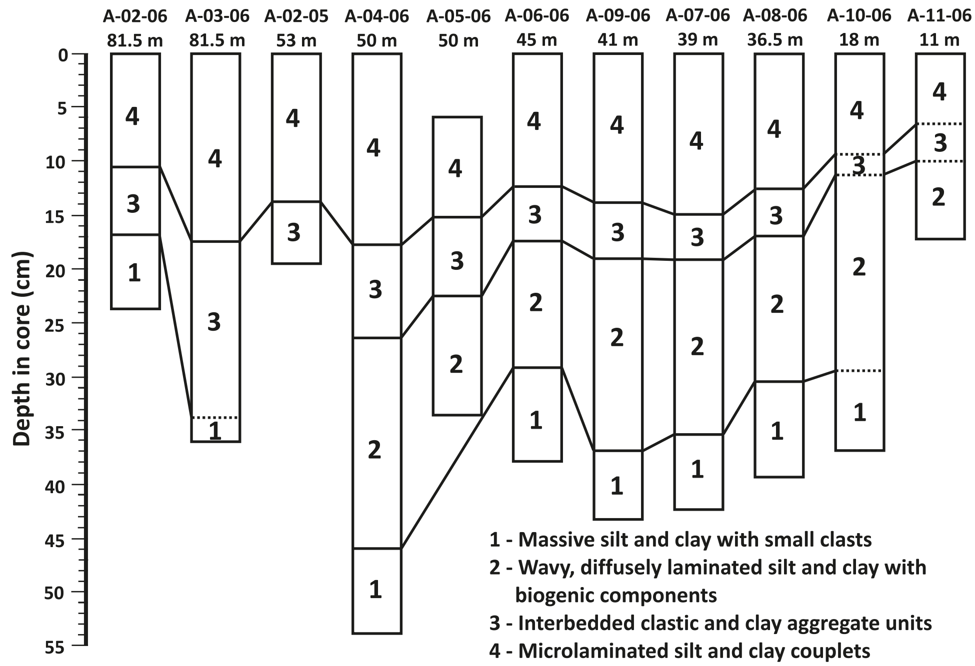


strands of organic matter and black granules (Fig. 7). Semi-quantitative elemental EDS analyses indicated that the ovoid features were predominantly composed of Si, Al, and Mg, with lesser amounts of K, Cl, Fe, Na, Ca, and Ti (Fig. 8), suggestive of smectite, likely montmorillonite (Anthony et al. 1995). The black granules, also notable in the other facies and sometimes concentrated within coarse units of laminated sections, were iron- and sulphur-rich (Fig. 8). Some of the black granules had a framboid structure identified as pyrite (Anthony et al. 1995; Fig. 9) and were commonly found along the edge of the ovoid–clay aggregates (Fig. 7). The base of facies 2 was typically delineated by darker sediment and a sudden cessation of the diffuse, wavy laminae. However, one core had a 2–3 mm thick, massive dark deposit at the base of this facies.

Structures remained vague in facies 3 but became progressively clearer upwards. The ovoid features were also prominent in this facies; and bands of these features were commonly interlaminated with submillimetre units of coarse, grey to red mineral grains, sometimes with detrital organic material (Fig. 5). Laminae were evident towards the top of this facies, but the ovoid features and related structures reduced the clarity of contacts and made laminae appear more diffuse relative to overlying facies 4. Facies 3 had the coarsest mean grain size (Table 1) and the sediments had brown and orange hues (7.76YR 3/6) with a green component towards the base. Several cores also contained a narrow section of massive sediments (30.6–32.6 cm in core A-04-06) with black grains or stains (<50–500 μm diameter).

The uppermost facies (facies 4) was composed mainly of well-defined, silt–clay couplets with orange and brown hues (7.96YR 4/8; Table 1; Fig. 5). The couplets ranged in thick-

Fig. 4. Facies 1–4 within the Lake A sedimentary record. Water depths from which the cores were obtained are listed. The top 6 cm of core A-05-06 was sampled in the field. Uncertain facies boundaries (due to diffuse sedimentation (shallowest two cores) or disturbance (core A-03-06)) are indicated by broken lines.



ness from <0.1–5 mm, with a mean thickness of 0.17 mm (five cores, n = 805–937 each). The couplets were interrupted occasionally by normally graded, thicker brown units and coarse, grey units with detrital organic matter. The well-defined microlaminae in facies 4 varied in thickness, composition, and colour, but the thin laminae precluded detailed observation of internal structure. Contacts were typically sharp and conformable between couplets. Simple couplets were typically composed of a fine unit overlying a lighter, coarser unit that sometimes contains detrital fragments of organic matter (Fig. 10). This pattern was evident in all cores collected below the oxycline and particularly in those obtained from water depths between 36.5 and 53 m. Based on grain-size data and microscopy, the coarse units typically contained silt, while the fine units were dominated by clay.

Laminae typically had a light to deep orange hue (darkest shade, 3.09 YR 2/6), although some sediments had minimal colouring (typical hue, 8.76Y 7/4). Couplets with a light hue were commonly diffuse in structure and had wavy contacts. Some couplets had light, translucent grains with an orange hue (1.89YR 9/2) within the lower unit that appeared friable and commonly discontinuous within the uppermost 3 cm of the sedimentary record, where these laminae were most common. Other couplets within facies 4 maintained the coarse–fine structure but were brown with little orange hue (5.01Y 4/4). Moreover, a pattern was notable of thin, vague laminae with a pale hue (8.76Y 7/4) overlain by a series of thicker, dark red–orange laminae (3.09YR 2/6) throughout the microlaminated sections of all cores collected below the oxycline (Fig. 11).

Some couplets consisted of poorly sorted sandy, diffuse detrital organic material and frequent black grains, overlain by a clay cap. These laminae were present in the lower part of facies 4 but were most common within facies 3. Thicker units (up to 5 mm) were sometimes normally graded, contained coarse mineral grains up to fine sand, and occasionally had detrital organic material at their base.

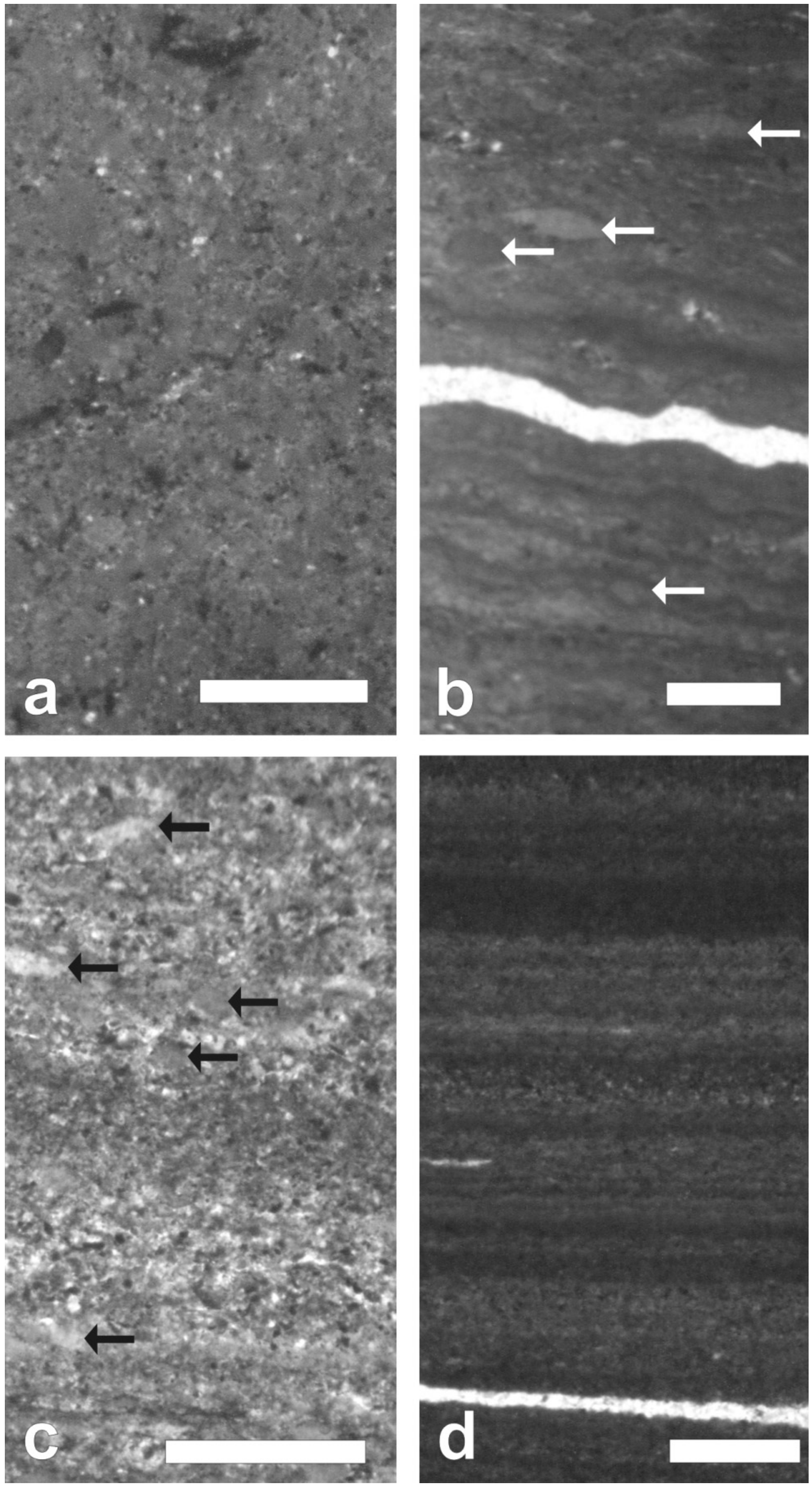
Mean couplet thickness thinned progressively, from 0.25–0.34 mm in deeper locations to 0.15 mm at shallower locations. Distal thinning was also apparent in the overall thickness of each sedimentary facies (Fig. 4). Dry density measurements from facies 2 to 4 ranged from 0.8 to 1.1 g·cm^{-3} but did not show any consistent trends. Hence, density corrections for compaction were not made to couplet thickness or depth measurements.

Sedimentary chronology

The uppermost section of the sedimentary record (facies 4) contained microlaminae. Based on the highly seasonal nature of sediment delivery to the lake and lake characteristics that promote sedimentary preservation, we hypothesize that these lamina couplets are varves (Tomkins et al. 2009).

Radioisotopic dating (^{137}Cs, ^{210}Pb) was conducted on core A-02-05 (Fig. 12) and radioisotopic ages were transferred to core A-04-06 using common marker beds because the uppermost 2 cm of core A-02–05 was disturbed. Measurable ^{137}Cs was present only in the uppermost 1.50 cm of the sedimentary record and did not show notable peaks. Similarly, low, unsupported ^{210}Pb levels precluded dating below 0.90 cm. However, modelled dates suggest that the top 0.90 cm of the sedimentary record represents sedimentation after 1969. Laminae counts indicate that 1963 coincides with peak ^{137}Cs abundance in the sedimentary record and two of the ^{210}Pb dates correspond with lamina counts while the third is slightly offset. This discrepancy could be due to slight differences in sedimentation in cores used, which would influence cross-correlation depths. Therefore, the laminae counts are corroborated by the radioisotopic age

Fig. 5. Photomicrographs of typical sedimentation in the Lake A sedimentary record, including (*a*) massive sediments in facies 1, (*b*) wavy and diffuse units in facies 2, (*c*) interbedded clastic and clay aggregate units in facies 3, and (*d*) microlaminae in facies 4. Arrows highlight ovoid features in (*b*) and (*c*). Scale bars indicate 1 mm.



models although the coarse resolution of the latter prohibits annual comparisons (Fig. 12).

The surface sediment had a radiocarbon date of 3215 ± 20 ^{14}C years BP, indicating a substantial influence of old carbon (Table 2). This date was subtracted from the other radiocarbon dates to provide a rough estimate of ages with-

Table 2. Summary of the ^{14}C ages for bulk sediment samples collected from various depths within the Lake A sedimentary record (core A-04-06).

Depth (cm)	Material dated	^{14}C age (years BP)	Calibrated (cal.) age range (1σ, years BP)[a]	Cal. and adjusted age (cal. years BP)[b]	Median cal. and adjusted age (cal. years BP)[c]	Laboratory sample No.
0.0–0.2	Bulk sediment	3215±20	3401–3450	0	0	UCIAMS–41208
8.2–8.4	Bulk sediment	4265±15	4836–4851	1410–1425	1418	UCIAMS–39015
13.3–13.4	Bulk sediment	6300±20	7177–7262	3751–3836	3794	UCIAMS–39018
29.2–29.3	Bulk sediment	6925±20	7710–7786	4284–4360	4322	UCIAMS–39016
46.4–46.5	Bulk sediment	8940±25	9950–10191	6525–6765	6645	UCIAMS–39017

Note: Dating was conducted at KECK Carbon Cycle AMS Facility (University of California, Irvine, California) and ^{14}C ages were calibrated using the IntCal04 calibration curve (Reimer et al. 2004) in the program Oxcal 4.0 (Bronk Ramsey 1995).

[a]The calibrated age ranges represent one standard deviation (1σ), which gives a probability of 68.4% that the true age of the sample falls within the age range listed.

[b]The calibrated age ranges were adjusted for the reservoir effect by subtracting the median value of the calibrated surface age range (3426 cal. years BP) from the calibrated age range for each sample.

[c]These values represent the median value for each calibrated age range with the median calibrated surface age (3426 cal. years BP) subtracted to account for the reservoir effect.

out the influence of old carbon, but the resulting ages for two samples from facies 4 remained ~990 and 3070 years, respectively, older than estimated varve ages.

Carbon and nitrogen

TOC and TN levels in core A-04-06 ranged from 0.4%–3.6% and 0.02%–0.3%, respectively (Fig. 6). Mean values within the profile were 1.9% TOC and 0.1% TN. The mean C/N ratio (based on atomic weight) was 17.3 within the sedimentary record and it ranged from 9.5 to 31.6. The highest C/N ratios occurred at the base of the sedimentary record within facies 1 while facies 4 contained some of the lowest values.

Sedimentary pellets

The sedimentary pellets of the Lake A sedimentary record are described in detail in Tomkins et al. (2009). Subrounded, cohesive sediment aggregates were prominent throughout facies 4 and upper facies 3, typically found as isolated individuals and composed of mostly grey (1.24GY 5/0) clastic grains, fine detrital organic material, and frequent black granules. The sedimentary pellets were <1–9 mm (long axis) and often loaded the underlying units (Fig. 13). At water depths <20 m, pellet material formed units that appeared to be aggregates of smaller pellets. A single grain-size analysis showed the pellets to be coarser than their surrounding sediment, and they had lower TOC and TN values and a notably higher C/N ratio (Table 1).

Discussion

Sedimentation in high arctic meromictic lakes

Sedimentation regimes in high arctic meromictic lakes reflect strong stratification and the influences of the dry, cold environment. Depositional processes were previously undocumented in Lake A although a number of studies have examined its limnology and geochemistry (e.g., Jeffries et al. 1984; Ludlam 1996; Belzile et al. 2001; Gibson et al. 2002; Van Hove et al. 2006). Despite the appearance of simple varves within the uppermost facies, the deposition of clastic and biogenic material in Lake A is highly complex. Most polar lakes have low productivity and are often dominated by allochthonous sedimentation (Lamoureux and Gilbert 2004). However, microbial activity within the water column and sediment of Lake A has actively influenced its sedimentary structures and produced discernable autochthonous deposits. Thus, sedimentation has been influenced by climate and fluvial and geomorphic processes in the catchment, as well as biogeochemical cycling, water column microbiota, and benthic microbial activity. Strong biological influences and features in dominantly clastic sedimentary sequences have also been infrequently documented in other high arctic lakes (Gajewski et al. 1997; Chutko and Lamoureux, in press). With multiple processes influencing sediment deposition, there was substantial temporal and spatial variation in the Lake A sedimentary profile, even within a few metres.

Despite these challenges, multiple core analyses of the sedimentation within the lake provide considerable insight into the different depositional influences within this unusual lacustrine environment. Four primary facies represent the progression from marine embayment through isolation to a highly stratified meromictic lake. Silt is consistently the dominant fraction of grain-size measurements (Table 1) although relative changes in sediment texture throughout the record are notable. The amount of sand in each facies is of particular interest, as sand was not present throughout the record. Sand concentrations within facies 1 and 4 suggest altered sediment sources or higher discharge intensity during these periods, compared with the finer-grained sediments of facies 2 and 3. Although no facies contained high levels of organic matter, the relatively low levels of TOC and TN in facies 1 and higher levels in facies 2 suggest a notable change in lake conditions spanning the same interval as the inferred progression from marine to lacustrine conditions while the progressive decrease in C/N values suggests increased contributions of aquatic organic matter to sediments and (or) decreased terrestrial organic inputs over time.

Sedimentary process studies have been conducted at nearby meromictic Lake C2 (35 km west), which is similar to Lake A (Retelle and Child 1996). Comparison of thin sections from both lakes suggests similar sedimentary features (Figs. 10, 12). At Lake C2, the main period of sediment delivery to the lake is confined to only a few days of maximum discharge when snowmelt drives sediment transport

Fig. 6. (*a*) Percentages of clay, silt, and sand; (*b*) mean and median grain size; (*c*) C/N (atomic) values, and (*d*) percentages of total organic carbon (TOC) and total nitrogen (TN) throughout the sediment profile of core A-04-06.

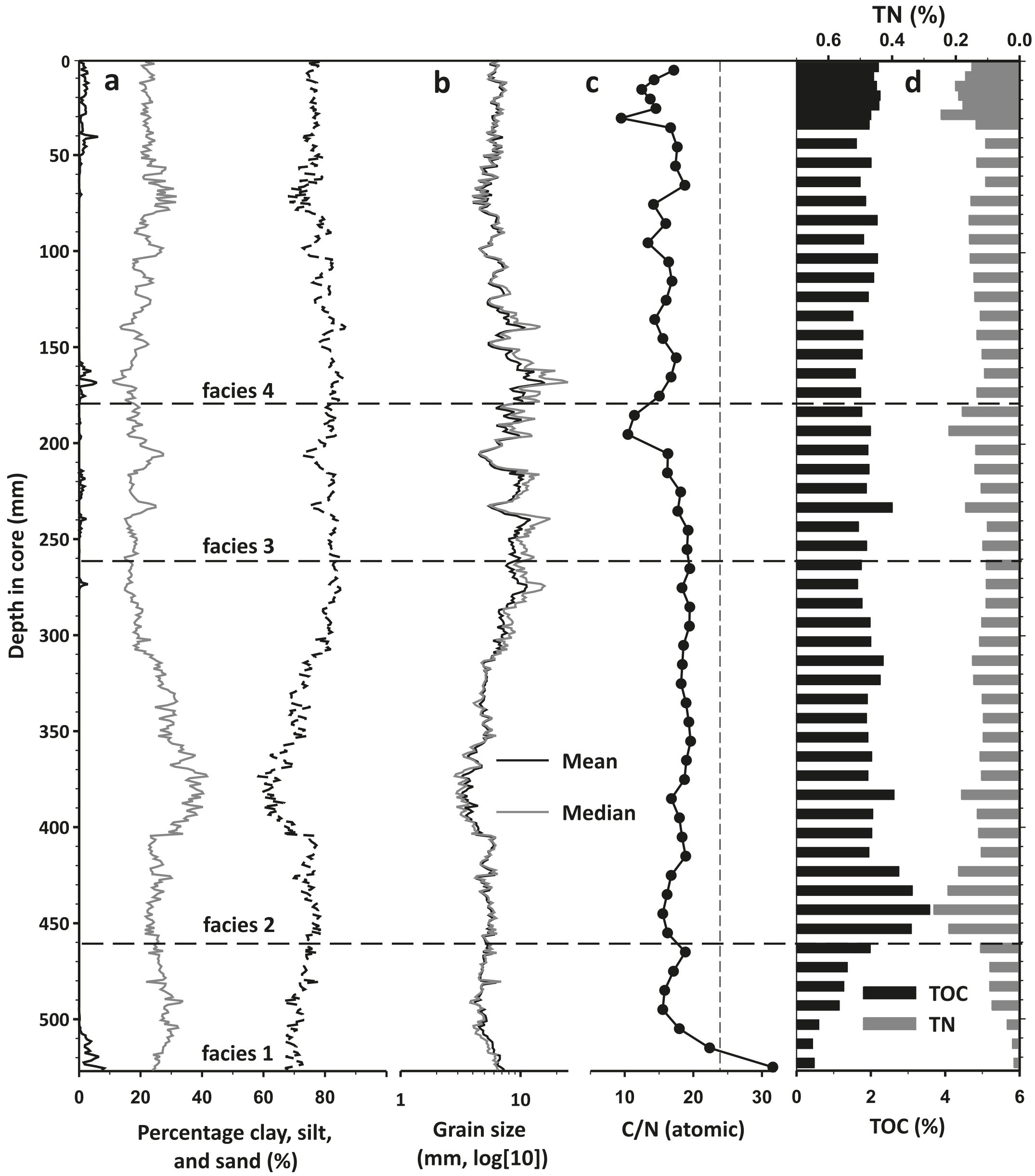


Fig. 7. Photomicrograph of ovoid, clay aggregates found in sections of the (*a*) Lake A and (*b*) Lake C1 sedimentary records. Scale bars indicate 250 μm.

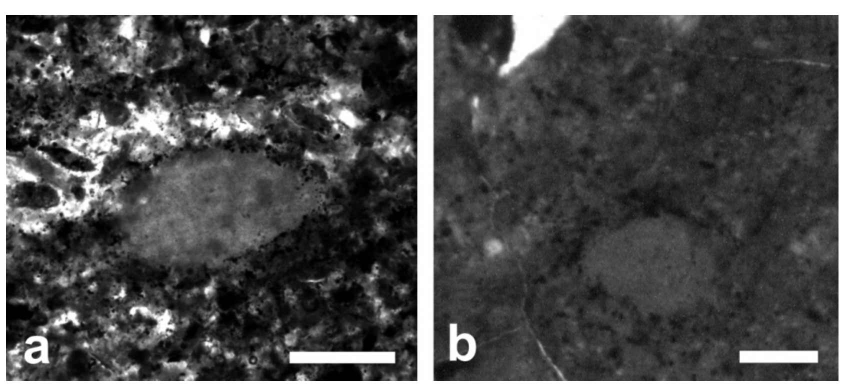


Fig. 8. Mean energy spectra for (*a*) 10 pyrite framboids and (*b*) five ovoid structures. Counts indicate the number of X rays detected at each energy level, and the elements corresponding to the peak counts are listed.

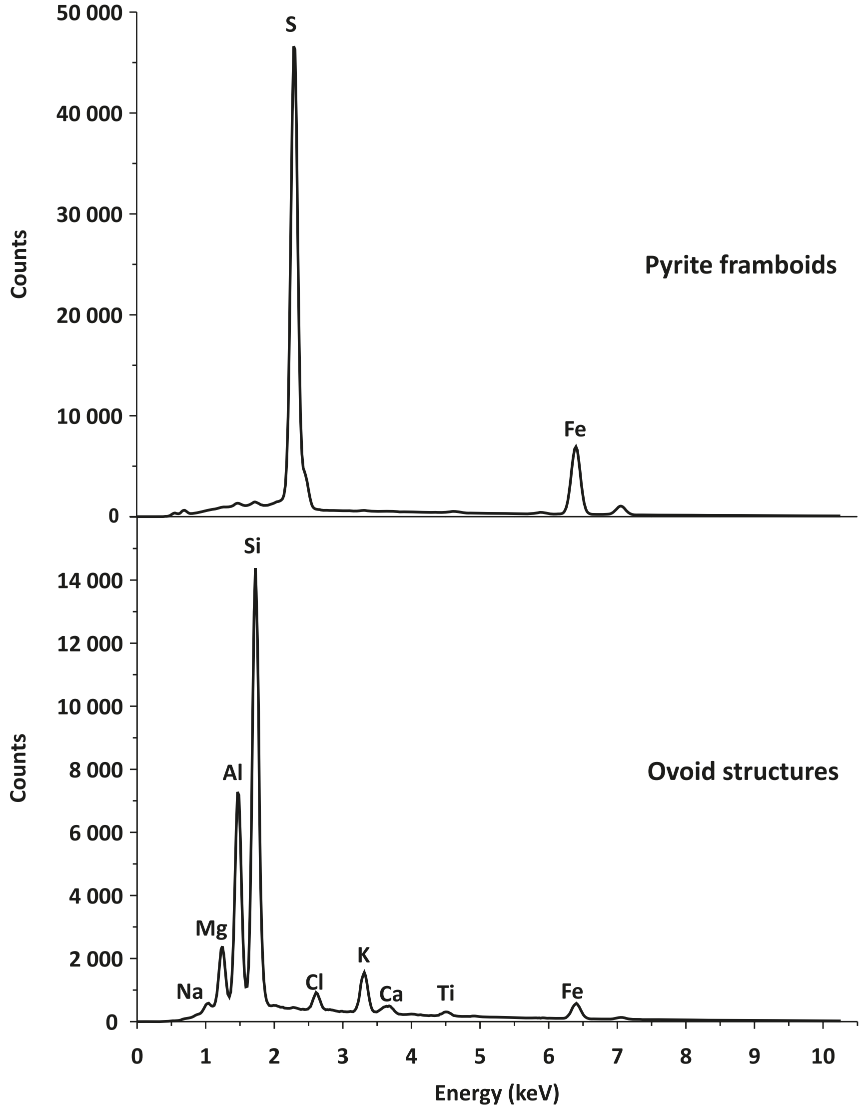


Fig. 9. SEM images of (*a*) large (3000× magnification) and (*b*) small (6000× magnification) euhedral pyrite framboids within microlaminated facies 4. Scale bars indicate 5 μm.

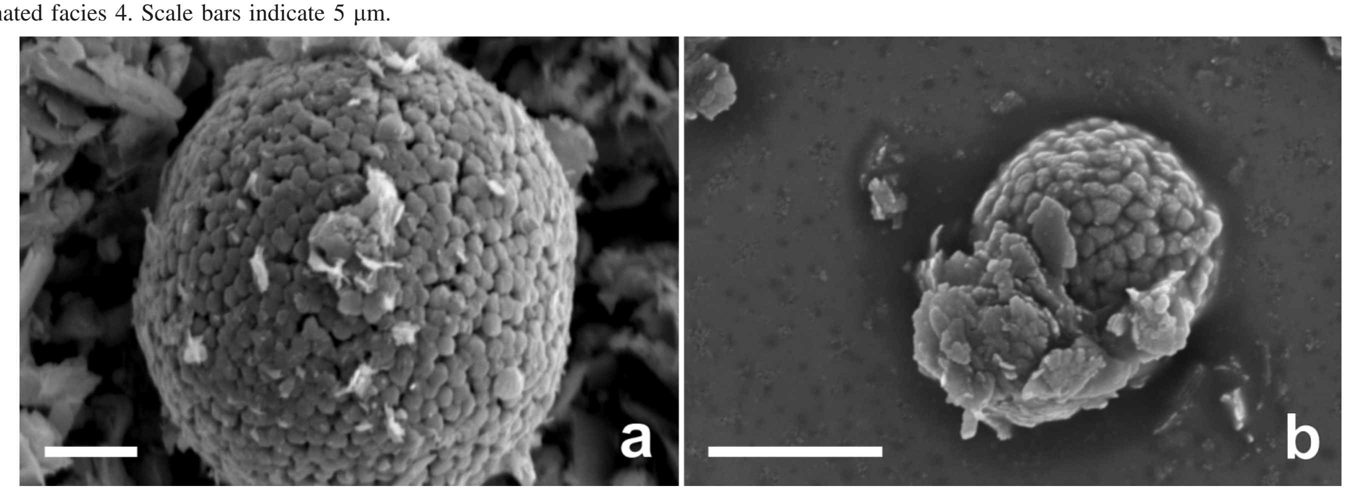


Fig. 10. Photomicrographs of varves composed of silt and clay couplets in facies 4 of cores (*a*) A-03-06 and (*b*) A-04-06. Note the black granules, which are either mineral grains or pyrite. Scale bars indicate 250 μm.

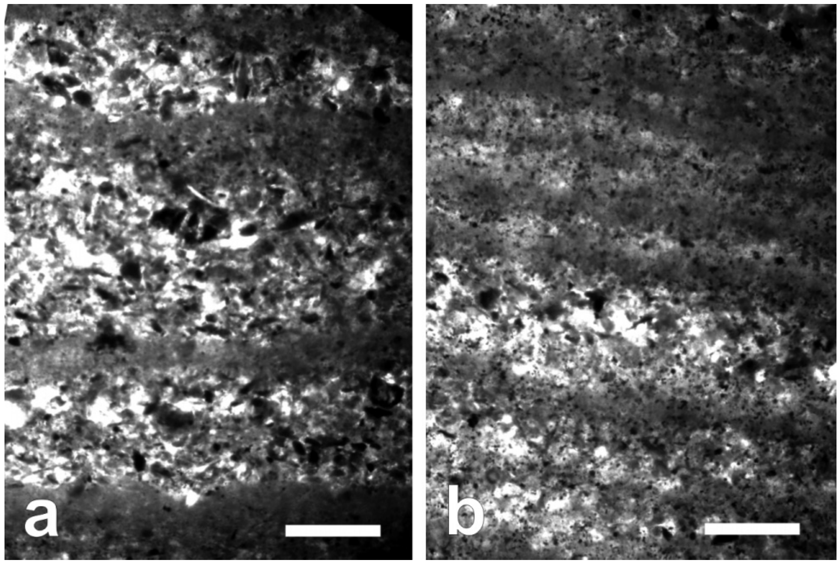
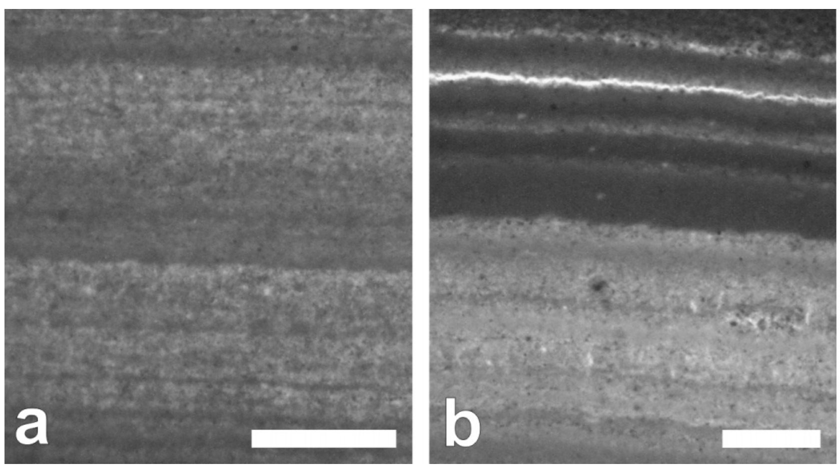


Fig. 11. Dark bands (with orange or red tint) overlying vaguer laminae with reduced pigmentation in (*a*) Lake A (two sequences) and (*b*) Lake C2 (one sequence). Scale bars indicate 1 mm.



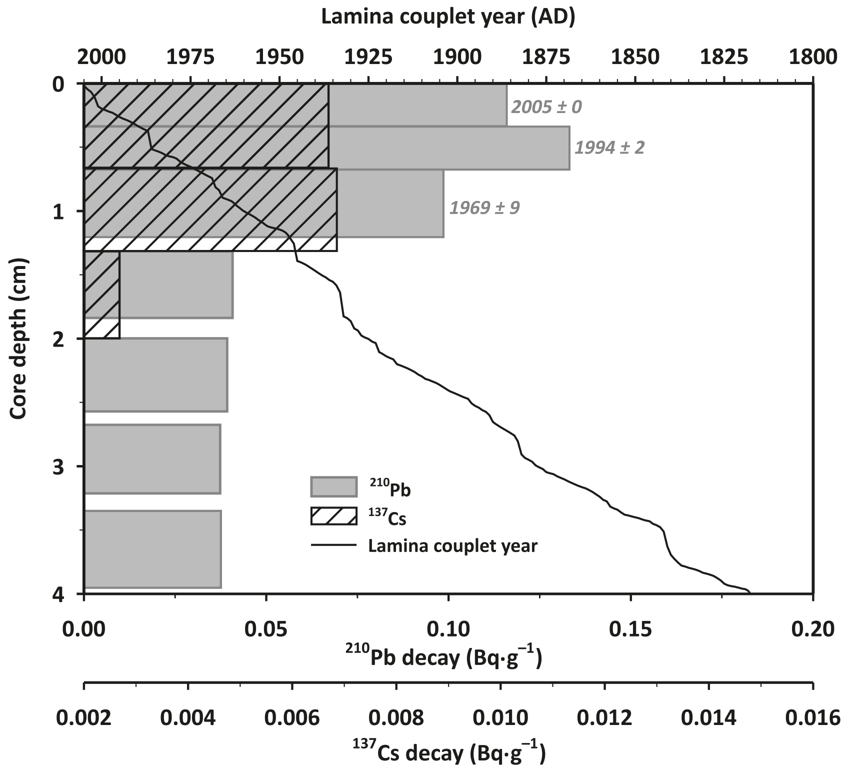
(Hardy 1996). Sediment inflow is distributed within overflows or interflows, which can sometimes reach into the monimolimnion when sediment concentrations are high (Retelle and Child 1996), followed by suspension settling as individual grains or flocs. Given the similar inflow and stratification at Lake A, sediment dispersion is likely also by similar overflow and interflow processes.

The northern slope of the Lake A basin, located between the delta and the outlet, contains laminated sediments that appear rarely disturbed by event deposits and contain the longest uninterrupted records studied. Sedimentation rates inferred from varve counts are low (~0.2–0.3 mm·year^{-1}), similar to those in Lake C2 (Lamoureux and Bradley 1996). Deep basin sediments are similar to those in the same locations in Lake C2 (Zolitschka 1996). The shallower sediments of both lakes appear to represent low-energy depositional environments dominated by suspension settling from overflows and interflows, while sediments from deeper locations indicate a more dynamic depositional environment subject to delta slumping and turbidites (Zolitschka 1996).

Differences in sediment structure based on location relative to the oxycline (~10–13 m depth) are apparent along the core transect. Sediments from below the oxycline contained microlaminae that were well preserved, likely owing to the absence of bioturbation and wind-mixing. Cores immediately below the oxycline (cores A-08-05 at 14.5 m and A-10-06 at 18 m) contained microlaminae that were more diffuse. A single core obtained from an oxygenated location (A-11-06 at 11 m) had the shortest laminated section and the most diffuse units of the cores studied. This core also had massive brown silt unit in the upper 0.5 cm, which suggests recent increased mixing activity at this location or a deepening of the oxycline. Diffuse laminae were also present in Lake C2 in cores obtained from locations above the oxycline (Lamoureux and Bradley 1996).

The characteristics of Lake A are conducive to varve preservation, including near-perennial ice cover, limited wind and wave activity, highly seasonal sediment delivery, and anoxic bottom waters. Although the temporal resolution of the radioisotopic data was limited by low sedimentation

Fig. 12. ^{137}Cs and ^{210}Pb decay compared with estimated ages from lamina couplet counts (modified from Tomkins et al. 2009). Estimated ^{210}Pb ages with estimated error (in years) are italicized. Radionuclide decay was measured in core A-02-05 and lamina counts were conducted on core A-04-06.



rates and low activities, the ^{137}Cs and ^{210}Pb profiles agreed with lamina couplet counts. Throughout the basin, individual laminae between marker beds in facies 4 were difficult to cross-correlate due to sedimentation differences and the extreme thinness of the units. Given such heterogeneity in sedimentation within Lake A, the use of multiple cores and marker beds was integral for analyzing sediment characteristics and spatial and temporal changes in sedimentation.

Further dating of the sedimentary record to verify lamina counts using radiocarbon yielded poor results, apparently owing to the influence of old carbon (Table 2). The lake likely contains a pool of old carbon that has been trapped in the monimolimnion, and this old carbon appears to affect carbon within the lake sediments. Modern terrestrial inputs of carbon also add complexity to the carbon store within the lake. Based on the inferred old carbon influence and offset between radiocarbon and varve ages at two depths, we suggest that the old carbon influence is not constant and we are unable to adequately account for its effects. This finding is not unique, as radiocarbon dates from other Arctic lakes have been found to be older than varve estimates (Zolitschka 1996) and not to correspond with isostatic rebound histories (Retelle et al. 1989).

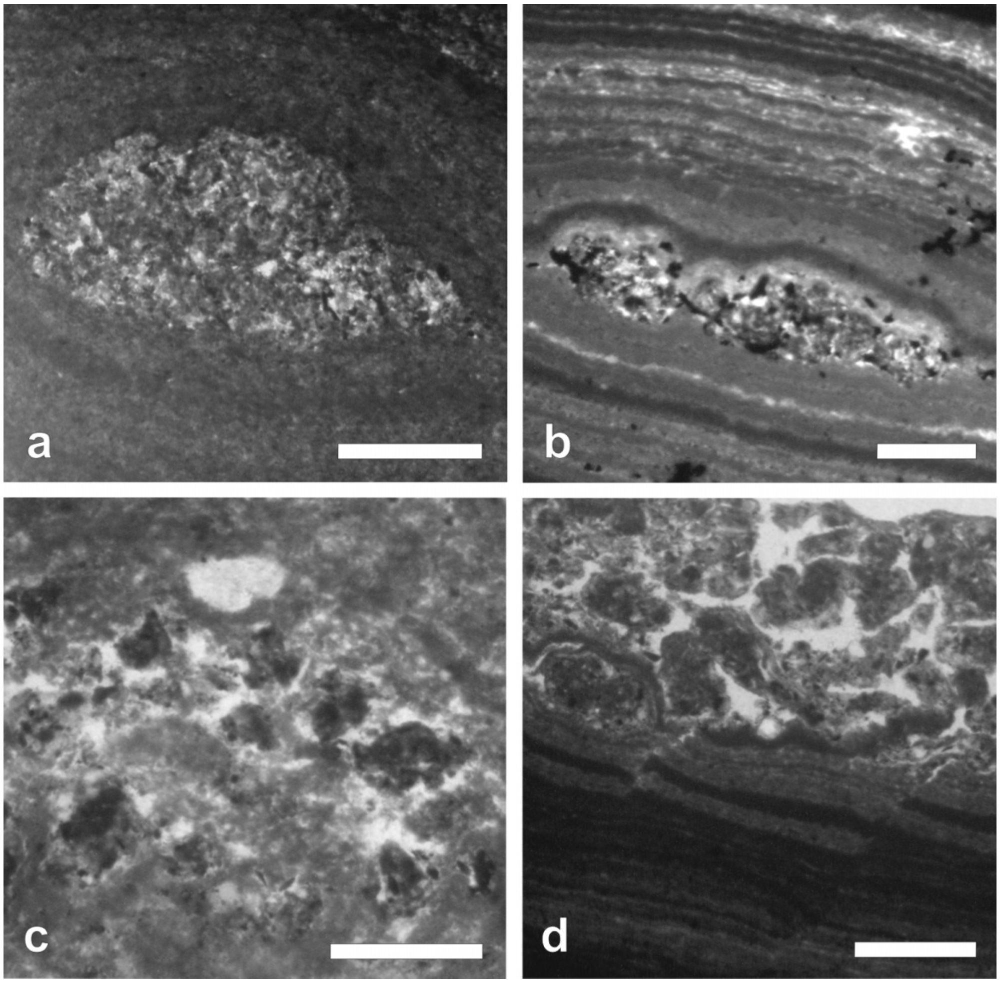
Chemical influences on varve sedimentation

Like other Arctic lakes with substantial iron availability in the catchment and (or) in the water column (e.g., Coakley and Rust 1968; Gilbert and Church 1983), the orange hue common within the Lake A lamina couplets is likely at least partly due to iron deposition and oxidization. Reduced iron (e.g., pyrite) was found throughout the sedimentary record, and particularly in facies 4 microlaminae, as black granules typically concentrated within coarse units.

Pyrite (FeS_2) is formed when sulphur-reducing bacteria in the monimolimnion reduce sulphates to form H_2S that reacts with Fe^{2+} in the water column to form iron monosulphides (Berner 1970). When mixing reaches into the upper monimolimnion and oxygenates it, anaerobic bacteria (e.g., green sulphur bacteria) die and release elemental sulphur into the water column (Berner 1970; Dickman 1979). This sulphur reacts with the iron monosulphides to form pyrite (Berner 1970). Photosynthetic pigments from the Lake A water column indicated the presence of green sulphur bacteria in anoxic waters, with a peak near 29 m water depth (Belzile et al. 2001; Van Hove et al. 2006). These bacteria utilize reduced sulphur compounds to photosynthetically fix carbon dioxide (Overmann 2001) and can provide the elemental sulphur needed to form pyrite in the water column when chemocline ventilation occurs. Pyrite in Lake A sediments appeared as individual pyrite granules clustered in spherical framboids (Fig. 10; cf., Kalliokoski 1974). The framboids did not appear to have crystal overgrowths that signify diagenetic pyrite formation, which suggests that they were formed in the water column (Suits and Wilkin 1998). Iron sulphide framboids, in addition to individual spherules, were also observed in another preliminary SEM–EDS study of the Lake A sedimentary record (M. Retelle, personal communication, 2008).

Ventilation events would require significant mixing and therefore ice cover reduction, but evidence suggests that this is infrequent. Intermittent observations of the Lake A ice from 1969–2008 indicate near-permanent ice cover, with

Fig. 13. Photomicrographs of ice-rafted pellets from within microlaminated sections of the (*a*) Lake A and (*b*) Lake C2 sedimentary records and unique pellets near the surface of the (*c*) Lake A and (*d*) Lake B sedimentary records. Note the warped units above and below the pellets in (*a*) and (*b*). Scale bars indicate 1 mm.



reduced ice cover conditions evident from satellite images in summer 2000, 2003, and 2006 (D. Mueller, personal communication, 2007) and complete ice removal in 2008. As well, the mesothermic water column profile does not vary substantially from year to year (Hattersley-Smith et al. 1970; Jeffries et al. 1984; Jeffries and Krouse 1985; Ludlam 1996; Belzile et al. 2001; Gibson et al. 2002). The only known exception was in August 2001 when the mixolimnion temperature profile showed near isothermy and had a reduced salinity gradient due to the exceptional reduced ice cover in the previous summer that would have permitted wind-induced mixing (Van Hove et al. 2006). Steps within the temperature profile were evident in 2005 and, to a lesser extent in 2006, indicating the progressive redevelopment of stratification in the temperature profile after the reduced ice cover of summer 2003 (Fig. 2). Additionally, a model of the development of the Lake A thermal profile suggests that the lake experienced substantial mixing 60–70 years ago (Vincent et al. 2008*a*).

In this context, the orange-hued sediments of Lake A likely reflect some degree of monomolimnion ventilation. Thick or notably dark orange–red laminae and pyrite-rich units likely reflect ventilation events that caused increased iron deposition from dissolved iron and bacteria mass mortality in the chemocline. The thick, dark orange laminae often exhibit basal load structures, which suggest relatively rapid sedimentation. Similarly, the frequent pattern of pale, diffuse laminae overlain by thick, dark orange or red laminae may indicate a period of chemocline ventilation after a phase of consistent upper monimolimnion anoxia (Fig. 11).

Biological influences on varve sedimentation

Biogenic structures are not commonly noted in polar lacustrine sedimentary records owing to extremely low sedimentation rates and organic contents (cf. Chutko and Lamoureux, in press). However, in meromictic lakes where the probability of lamina preservation is high and mineral sedimentation rates are often low, organic deposits can be discerned (Lamoureux and Gilbert 2004). In Lake A, microbial mats were present in shallow littoral locations along the shoreline of the delta (A. Jungblut, personal communication, 2008) and prostrate microbial mats were evident within anoxic waters at 20 m water depth (D. Andersen, personal communication, 2007). A bright green microbial mat was also found on the surface of a core recovered from 18 m water depth, and moss tufts were found at shallower depths.

Filamentous microbial mat material has also been observed floating in the summer moat area and in sampling holes through the ice cover at nearby Lake C2 (M. Retelle, personal communication, 2008).

The extent of microbial mat features along the Lake A bottom is unknown though (Fig. 3). Apart from the shallowest mats growing in water along the delta, none of the benthic organic features outwardly resemble the microbial mats found in comparable Antarctic lakes (e.g., Parker et al. 1981; Simmons et al. 1993; Vopel and Hawes 2006). In particular, Lake A is deeper than these lakes and has a thinner ice cover, which would affect both the types of microbes present and the extent of benthic microbial activity (Simmons et al. 1993; Wharton et al. 1993).

Modern sedimentation in the lake is sufficiently high for the preservation of annual laminae but does not preclude benthic microbial activity in some areas of the lake. In the water column, picocyanobacteria and green sulphur bacteria are active well into the monimolimnion (Belzile et al. 2001; Van Hove et al. 2006). The most recent sediments of some cores have lamina structure and composition that is uncommon elsewhere in the record, with friable coarse units with apparent biogenic components and laminae with horizontal discontinuities in the uppermost 1–2 cm. Similar features have been noted in other sedimentary settings, where the tearing of thin microbial mat layers or similar microbially induced sedimentary structures (Noffke et al. 2001) and subsequent burial might explain the laminae disruptions (Schieber 1999). As microbes are always active within the water column, some of these units may be the result of biogenic deposits from activity within the water column rather than benthic activity, especially in deeper locations. However, without more information about the extent of microbial mats in the lake or bacteria within these uppermost sediments, the exact processes involved in their formation remain unresolved.

Evidence for microbial activity is also present earlier in the sedimentary record. Traces of the organisms that form biolaminae (Gerdes et al. 1991) often are not consistently preserved for more than a few hundred years within a sedimentary record (Krumbein and Cohen 1977), which can make positive sedimentary identification of a mat deposit or biolaminae difficult (Schieber 1999). In facies 2 and 3, relatively coarse units that sometimes included detrital organic material are interbedded with thin biogenic units. These units are composed of finer material with ovoid clay aggregates that commonly have pyrite framboids along their edges, and sometimes, connecting thin bands of black granules (presumably pyrite, Fig. 7). Both facies 2 and 3 also have wavy or crinkled iron-rich (red and black) bedding, potentially indicative of a biologically stabilized surface (Schieber 1999; Noffke et al. 2001).

The formation of the ovoid clay aggregates is not clear, but they may represent authigenic clay precipitates, possibly formed within the water column. In both river and freshwater lake environments, bacteria in biofilms have been observed to act as nuclei for the precipitation of typically amorphous (Fe, Al) silicates (Konhauser and Urrutia 1999; Konhauser 2006). Iron sulphides are also commonly formed alongside these clays (Ferris et al. 1987), which may explain the pyrite crystals observed around some of the ovoid clay features. However, this process was described at the cellular level and aggregates of the precipitated clay would have to develop to produce the relatively large ovoid structures at Lake A. Additionally, this process was described in a freshwater environment while the monimolimnion in Lake A is saline. Despite these issues, all ovoid features studied using EDS showed the same elemental composition and detrital clay grains would likely exhibit more variety in elemental composition. Therefore, although many characteristics of the ovoid clay features suggest a biogenic origin, we have as yet been unable to directly associate them with bacterial remains.

Sedimentary pellets

Two possible sources for the coarse sediment aggregates found in all cores have been determined (Tomkins et al. 2009). Cryoconite deposits can result from microbial cohesion of sediment in ice-surface cavities formed by preferential melt by sediment brought onto the ice by aeolian or fluvial processes (Priscu et al. 1998; Fountain et al. 2004). Such holes have not been observed at Lake A and aeolian deposits appear to be minimal, but cryoconite hole development remains a possible pellet formation process (Tomkins et al. 2009).

The available data best support ice-rafting as a pellet formation mechanism (Tomkins et al. 2009). The pellets may originate from littoral sediment scavenging by anchor ice, which has been observed to form at the bottom of the lake's summer moat. Alternatively, if the ice cover were to come into contact with littoral sediments during fall or winter, sediment could adhere to the ice and become incorporated into the ice cover (Smith 2000). In either case, the pellets would be transported to across the lake by mobile ice pans during reduced ice cover periods and deposited during melt (Tomkins et al. 2009).

In 1986, pellets were observed in the basal part of the Lake A ice cover (M. Retelle, personal communication, 2008). In spring 1999, sediment aggregates up to 2 cm in diameter were observed in within the top 1 m of the 2 m thick ice cover (Belzile et al. 2001). Either of the two suggested processes could have potentially formed these pellets. As reduced ice cover would be required to deposit pellets formed by ice-rafting or aeolian processes, the sedimentary pellet record is representative of past ice cover variability (Tomkins et al. 2009).

The sedimentary history of Lake A

Facies 1 — Holocene marine sedimentation

Lake A began as an embayment of the Arctic Ocean as ice retreated after the last glacial maximum and the sea transgressed to the Holocene marine limit (Hattersley-Smith et al. 1970). Marine limit (~72 m a.s.l.) was reached before ~8600 years BP (Lemmen 1989). Sediments deposited in the embayment contain considerable fine material but also sand and pebbles from glacial meltwater entering the bay (Lemmen 1989). As isostatic rebound progressed and the northern Ellesmere ice shelves formed under cooling temperatures, the lake became isolated from marine waters between 2500–4450 years BP (Lyons and Mielke 1973; England and Stewart 1985; Bradley et al. 1996).

Facies 2 — late Holocene initial isolation

Lake A emerged from the sea with continued isostatic rebound. During this process, sediment inputs became nearly devoid of sand, aquatic productivity increased, and biologically influenced sedimentary features resulted in increased TOC and TN (Fig. 6; Table 1). The region became increasingly cold during the late Holocene (Bradley 1990), and reduced runoff and more persistent ice cover may have played roles in limiting sediment inputs to the lake. Sedimentation remained low enough to permit the deposition of only diffuse sedimentary units, and biolaminae formed as microbially derived biogenic units were deposited and covered by seasonal to periodic sediment inflows (Fig. 7).

Facies 3 — late Holocene change in sedimentation

Coarser sediments were deposited at this time, indicating either new catchment sediment sources or increased discharge into the lake (Table 1). At present, the catchment contains a plateau with a glacier immediately adjacent to the watershed divide. During this period, the glacier may have extended into the catchment and meltwater may have delivered coarser and more episodic clastic sedimentation to the lake. With this new sedimentation regime, microbial communities had to adapt to the new conditions and biogenic deposits were reduced compared with clastic material. The interbedding of coarse and ovoid clay aggregate-rich fine units became more clearly defined, and the inferred biogenic units gave way to dominantly clastic sedimentation in the late stages of this facies (Fig. 7).

Facies 4 — late Holocene varve sedimentation

Lake A attained the necessary conditions to consistently preserve varves when clastic sedimentation dominated over microbially derived inputs and, thus, well-defined clastic laminae with some biogenic components were deposited (Fig. 7). The coarse sedimentary units with detrital organic matter that were common in facies 3 became infrequent, suggesting a lower energy regime. Silt and clay couplets dominated the sedimentary record although inferred oxygen incursions into the upper monimolimnion were common, and the mortality of green sulphur bacteria in the upper anoxic waters contributed to iron-rich sediments. The frequent presence of sedimentary pellets within this section also suggests periods of reduced ice cover (Fig. 13).

Comparative sedimentology of High Arctic meromictic lakes

Lake A is one of only a dozen known meromictic lakes in the Canadian High Arctic, including neighbouring lakes B, C1, C2, and C3 (Van Hove et al. 2006) and Romulus Lake (Davidge 1994) on Ellesmere Island, Lake Sophia on Cornwallis Island (Pagé et al. 1984), and Garrow Lake on Little Cornwallis Island (Ouellet et al. 1989). Sedimentation processes reflect differences in ice cover regimes, local relief, and sediment availability; but common features are evident among some their sedimentary records (Table 3). Of these lakes, only lakes A and C2 have varve structures confirmed by radioisotopic analyses (Lamoureux and Bradley 1996; this study), but others potentially also contain varved sediments.

The sedimentary profiles of lakes B, C1, C2, and C3 had microlaminae that are commonly orange hued. The sedi-

Table 3. Summary of regional meromictic lake locations, morphometry, water column properties, and presence of key sedimentary structures identified using the Lake A sedimentary record.

Lake characteristics[a]				Water column properties[a]		Sedimentary structures				
Lake name	Location	Area (km^2)	Catchment area (km^2)	Specific conductivity peak ($\mu S \cdot cm^{-1}$)	Total iron peak ($mg \cdot L^{-1}$)	Microlaminated couplets	Orange–red hue	Ovoid features	Pellets	Black granules
A	83°00′N, 75°30′W	4.9	36.0	49000	2.00	X	X	X	X	X
B	82°58′N, 75°30′W	0.9	5.0	43000	?[b]	X	X		X	X
C1	82°51′N, 78°12′W	1.1	3.3	40000	0.03	X	X	X		X
C2	82°50′N, 78°05′W	1.8	23.5	44000	12.10	X	X		X	X
C3	82°48′N, 78°05′W	1.7	180.0	250	0.49	X	X			
Romulus	79°53′N, 85°07′W	4.4	28.0	98000	71.00	X	X	?	?	?

[a]Sources for lake characteristic data: lakes A and B, this study; lakes C1, C2, and C3, Van Hove et al. 2006; Romulus Lake, Davidge 1994. Sources for water column property data: Lake A, lakes C1, C2, and C3, and Romulus Lake, Van Hove et al. 2006; Lake B, Ludlam 1996.
[b]Question marks indicate information that is unavailable.

ments of Romulus Lake had thicker couplets (0.6–1.2 mm thick) than those of Lake A, but they often had a red hue due to iron oxides (Davidge 1994). The pattern of light, diffuse varves below a series of thick, dark orange or red varves found in Lake A was also evident within the microlaminated portions of some Lake C2 cores (Fig. 11). Similarly, Lake C2 had wavy deposits that appear friable and are similar to biogenic deposits in the Lake A surface sediments. Microbial mat material has also been observed in Lake C2 (M. Retelle, personal communication, 2008).

Small black granules, similar to those identified as pyrite or mineral grains in the Lake A sediments, were also present in lakes B (although not as commonly), C1, and C2. Green sulphur bacteria were identified within the water column of Lake C1 (Van Hove et al. 2006) and may influence pyrite deposition during chemocline ventilation events in this lake. The paucity of black granules in the sedimentary record of Lake C3 may be due to the lake's nearly freshened state (Van Hove et al. 2006), which would limit anaerobic biological communities and pyrite formation analogous to that in Lake A. The sub-rounded pellets of coarse lithic material with organic matter were also present in lakes B and C2 (Fig. 13), and the ovoid clay aggregates (Fig. 7) found in Lake A facies 2 and 3 were present within diffuse sediments of Lake C1 although infrequently.

Comparison of Lake A sedimentary characteristics with those of other arctic meromictic lakes demonstrates the likelihood of common sedimentation processes. The records of pyrite deposition and its associated chemical and biological activities in these lakes may aid in further understanding their limnology and sedimentology and provide additional paleoenvironmental information.

Conclusions

The distinct limnology, stratification, and perennial ice cover of meromictic Lake A and its chemical and biological processes have produced a complex sedimentary record that incorporates clastic, chemical, and biogenic components. Four different facies represent various stages of the lake's development from an embayment of the Arctic Ocean to a stratified meromictic lake. Contributions by microbial communities to the sedimentary record have varied over time with early biogenic markers, including wavy, diffuse laminae and ovoid clay aggregates, yielding to more clastic deposits with clearer structure within the most recent sediments. The uppermost sediments contain varves formed under anoxic conditions that may be used to develop paleoenvironmental information.

Other sedimentary features show the diversity and complexity of sedimentation processes in Lake A. Sedimentary pellets are found only in the uppermost sediments but provide information on past ice cover variability. Iron is an important component of Lake A limnology and sedimentology, as evidenced by iron-rich deposits. While some iron is deposited by physical processes, black granules of pyrite and mineral grains are found in varying amounts in all facies. The former suggests biological and chemical inputs to sedimentation, at least in the uppermost sediments. Moreover, particularly iron-rich deposits may be indicative of reduced ice cover periods when wind-mixing allows for partial ventilation of the upper chemocline and results in pyrite precipitation.

Features in the sedimentary record of other meromictic lakes on northern Ellesmere Island show many similarities to Lake A, and these results suggest these sedimentary environments appear to be more complex than previously thought. Hence, their sedimentary records hold potential for detailed limnological, hydrological, and climatological records.

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