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Glaciolacustrine sediments and Neoglacial history of the Chephren Lake basin, Banff National Park, Alberta

Les sédiments glaciolacustres et l’évolution néoglaciaire du bassin du Chephren Lake, dans le parc national de Banff, en Alberta

GlaziallimnischeSedimente und neoglaziale Geschichte des Chephren Lake-Beckens im Nationalpark von Banff, Alberta

Randy W. Dirszowsky and Joseph R. Desloges

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Article abstract

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GLACIOLACUSTRINE SEDIMENTS AND NEOGLACIAL HISTORY OF THE CHEPHREN LAKE BASIN, BANFF NATIONAL PARK, ALBERTA

Randy W. DIRSZOWSKY, Department of Geography, University of Toronto, Toronto, Ontario, M5S 3G3, randy@geog.utoronto.ca.

Joseph R. DESLOGES, Department of Geography, University of Toronto, Toronto, Ontario, M5S 3G3.

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ABSTRACT Modern and historical sedimentation in Chephren Lake are examined in order to assess the relations between glacier activity, sediment production, and the lacustrine depositional record. Bottom sediment data and lake morphology indicate that sediments in the distal part of the lake primarily settled from suspension and that glaciers are the most important source. A 4.3 m core obtained from the distal sediments reveals that accumulation of fine, glacially-derived material has increased since at least 2420 BP. Simple geochemical indicators reflect this and support regional evidence for progressive (though punctuated) climate deterioration through the Neoglacial period. Distinct rhythmite sequences (especially beginning *ca.* 3460, 2330, 1470 and 530 BP) are thought to represent minor glacier retreats which help define separate phases of Neoglacial advance identified by previous workers. In contrast, increasing slope stability indicated by a reduction in graded sand and clast facies may be specific to slopes overlooking the coring site.

RÉSUMÉ *Les sédiments glaciolacustres et l'évolution néoglaciaire du bassin du Chephren Lake, dans le parc national de Banff, en Alberta.* La sédimentation moderne et passée est étudiée ici dans le but d'établir les relations entre l'activité du glacier, la production de sédiments et la mise en place de dépôts lacustres. Les données sur les sédiments de fond et la morphologie lacustre montrent que les sédiments en suspension de la partie distale du lac ont été les premiers à se déposer et que les glaciers en sont la princiaple source. Une carotte de 4,3 m recueillie dans les sédiments distaux révèle que l'accumulation du matériel fin d'origine glaciaire a augmenté depuis au moins 2420 BP. Les indicateurs géochimiques traduisent cette situation et reflètent, comme le font les indices régionaux, une détérioration climatique progressive (plus ou moins accentuée) au cours du Néoglaciaire. Des séquences de rythmites distinctes (surtout à partir de 3460, 2330, 1470 et 530 BP) semblent traduire des retraits glaciaires mineurs ; elles contribuent à mieux définir des phases distinctes de récurrence néoglaciaire dèjà identifiées par d'autres chercheurs. Par contre, la statibilité accrue des versants reflétée par la réduction des faciès composés de sables grano-classés et de gros fragments pourrait être caractéristique des versants dominant le site de carottage.

ZUSAMMENFASSUNG *Glaziallimnische Sedimente und neoglaziale Geschichte des Chephren Lake-Beckens im Nationalpark von Banff, Alberta.* Die moderne und vergangene Sedimentierung im Chephren Lake wird untersucht, um die Beziehungen zwischen Gletscheraktivität, Sedimentproduktion und der Ablagerung von Seesedimenten festzustellen. Die Angaben zu den Ablagerungen auf dem Grund und die Morphologie des Sees zeigen, daß Suspensions-Sedimente im distalen Teil des Sees sich zuerst abgelagert haben und daß Gletscher deren wichtigste Quelle sind. Ein Bohrkern von 4,3 m von den distalen Sedimenten läßt erkennen, daß die Akkumulation von feinem Material glazialen Ursprungs seit mindestens 2420 v.u.Z. zugenommen hat. Einfache geochemische Indikatoren spiegeln dies und stützen den regionalen Beleg für eine progressive (wenn auch nicht kontinuierliche) Klima-Verschlechterung in der neoglazialen Periode. Deutlich unterschiedene Sequenzen von Rhythmiten (vor allem ab *ca.* 3460, 2330, 1470 und 530 v.u.Z.) bezeugen wohl unbedeutendere Gletscherrückzüge; sie helfen dabei, getrennte Phasen neoglazialer Vorstöße zu definieren, die frühere Forscher indentifiziert hatten. Dagegen könnte die wachsende Stabilität der Hänge, welche an einer Abnahme an sortiertem Sand und an groben Fragmenten erkennbar ist, für die Hänge über dem Bohrgelände charakteristisch sein.

INTRODUCTION

The main difficulty associated with reconstructing Holocene glacier chronologies, and glacial chronologies in general, is the lack of continuous terrestrial geomorphic and paleontologic sequences. In the case of Holocene environments in the Canadian Cordillera, this situation is largely due to the fact that the last major glacier advance was generally the most extensive. Sediment reworking by ice has eradicated, obscured or buried terrestrial evidence of earlier activity (Luckman and Osborn, 1979; Osborn and Luckman, 1988; Desloges and Ryder, 1989).

In some cases this difficulty has been overcome by examination of proglacial lacustrine deposits which are thought to provide a more continuous, and possibly direct, indication of glacier activity. Recently, the approach has been applied to extant lakes in alpine (*e.g.* Leonard, 1986, 1997; Karlén and Matthews, 1992; Reasoner *et al.*, 1994; Souch, 1994) and polar environments (*e.g.* Lemmen *et al.*, 1988; Björck *et al.*, 1993) where sediment yield was continuous during the Holocene epoch. In most cases, interpretations of glacial history and climate change have been based on the assumption that periods of increased sedimentation correspond to increased ice extent. Climatic deterioration and increased ice extent are supposed to lead to higher sediment yields and therefore thicker and more clearly stratified sediments. More energetic flows deliver coarser textured sediments which are lower in organic content due to their glacial origin. Several studies have indicated that sediment yield depends on the stage of a glacier advance-retreat cycle, and may lag the responsible glacier fluctuation (*e.g.* Leonard, 1986; Clague, 1986). Highest rates of sedimentation are thought to be associated with glacier retreat, exposure of subglacial debris and increased meltwater stream discharge.

Where sediments (especially varved sediments) provide sufficient resolution to clarify the above temporal relations, the record has invariably been restricted to decades or centuries due to the logistics of long core retrieval at suitable sites (*e.g.* Sturm and Matter, 1978; Desloges, 1994). This paper describes sediments obtained from a glacier-fed lake in a small drainage basin in Banff National Park. Relative to lacustrine records examined within larger catchments in the southern Canadian Cordillera, the length of record and resolution are improved due to moderate rates of accumulation. The close proximity to glaciers and the absence of intervening storage of fine sediment allow examination of direct sedimentary links between the lake and the glacierized contributing basin. Glacier changes are also documented directly from terrestrial sediments and vegetation for comparison with the lacustrine sediments and with regional evidence of Holocene glacier fluctuations.

THE STUDY AREA

Chephren Lake is situated at an elevation of approximately 1700 m a.s.l. in the main ranges of the Rocky Mountains immediately east of the continental divide (51_, 51' N, 116_, 39' W; Fig. 1). The contributing basin (including Chephren Lake) covers 11.6 km^2 and is tributary to the Mistaya River, which drains northward into the North Saskatchewan River. Approximately 2.1 km^2 (18%) of the Chephren basin is currently glacier covered compared to 11% for the larger Mistaya basin. No continuous discharge data are available for this small catchment, but annual runoff for the Mistaya River basin averages 850 mm which is much higher than the regional average of 380 mm (Water Survey of Canada, 1991) due to relatively high elevations and glacier cover.

Chephren Lake is approximately 3 km long, has a surface area of 1.3 km^2, and thus occupies a substantial portion (11%) of the catchment (Fig. 2). Water surface elevation is controlled by a till and colluvium mantled bedrock rise which separates it from the main Mistaya River valley. The majority of the contributing catchment consists of unvegetated or minimally vegetated bedrock surfaces (Fig. 2). Planimetrically these surfaces account for 56% of the basin, but actual bedrock exposure is somewhat greater due to the high relief. The lake itself, the glacier forefield, and part of the structural bench supporting modern cirque glaciers, are underlain by Lower Cambrian Gog quartzites (Fritz *et al.*, 1992). With the exception of the peak of Mount Chephren, this grey and red tinted material also comprises the slopes directly overlooking the west and extreme southeast of the lake (Fig. 2). In contrast, the steep headwalls of the basin and most of the glacier covered source areas are composed of dark grey carbonates and shales of the Middle Cambrian Mount White/Cathedral and Stephen/Eldon formations.

The head of Chephren Lake abuts a largely unvegetated glacial forefield of coarse outwash debris, undulating ground moraine and a complex of lateral and end moraines associated with two cirque glaciers now confined to bedrock benches approximately 0.5 km up-valley. Several niche glaciers occupy upper headwall positions. Forefield moraines are comparable in form and state of plant colonization to Little Ice Age moraines found throughout the Rockies (Osborn and Luckman, 1988). Their size and position indicate that ice was fully advanced to the lake margin recently. Although exact dates are not available, increment cores from over 60 trees in and around the moraines provide approximate ages of forefield surfaces (unpublished data). If an ecesis interval of 15 years for *Abies lasiocarpa* and *Picea engelmannii* is assumed (McCarthy and Luckman, 1993), and appropriate height-age corrections applied (McCarthy *et al.*, 1991), then the outermost moraine ridges stabilized more than 140 years ago or about 1850 A.D. Several inner moraines were stabilized following a final glacier retreat between 1890 A.D. (eastern glacier) and 1900 A.D. (western glacier).

METHODS

During the summer field season of 1992, the bathymetry of Chephren Lake was assessed using a Raytheon 200 kHz echosounder along 14 km of transects (Fig. 3). Bottom surface sediments were sampled throughout the lake (Fig. 3) using an Ekman sampler. Thirty-one evenly spaced samples were saved as bulk samples, and eight of these were also preserved as short cores, yielding undisturbed samples

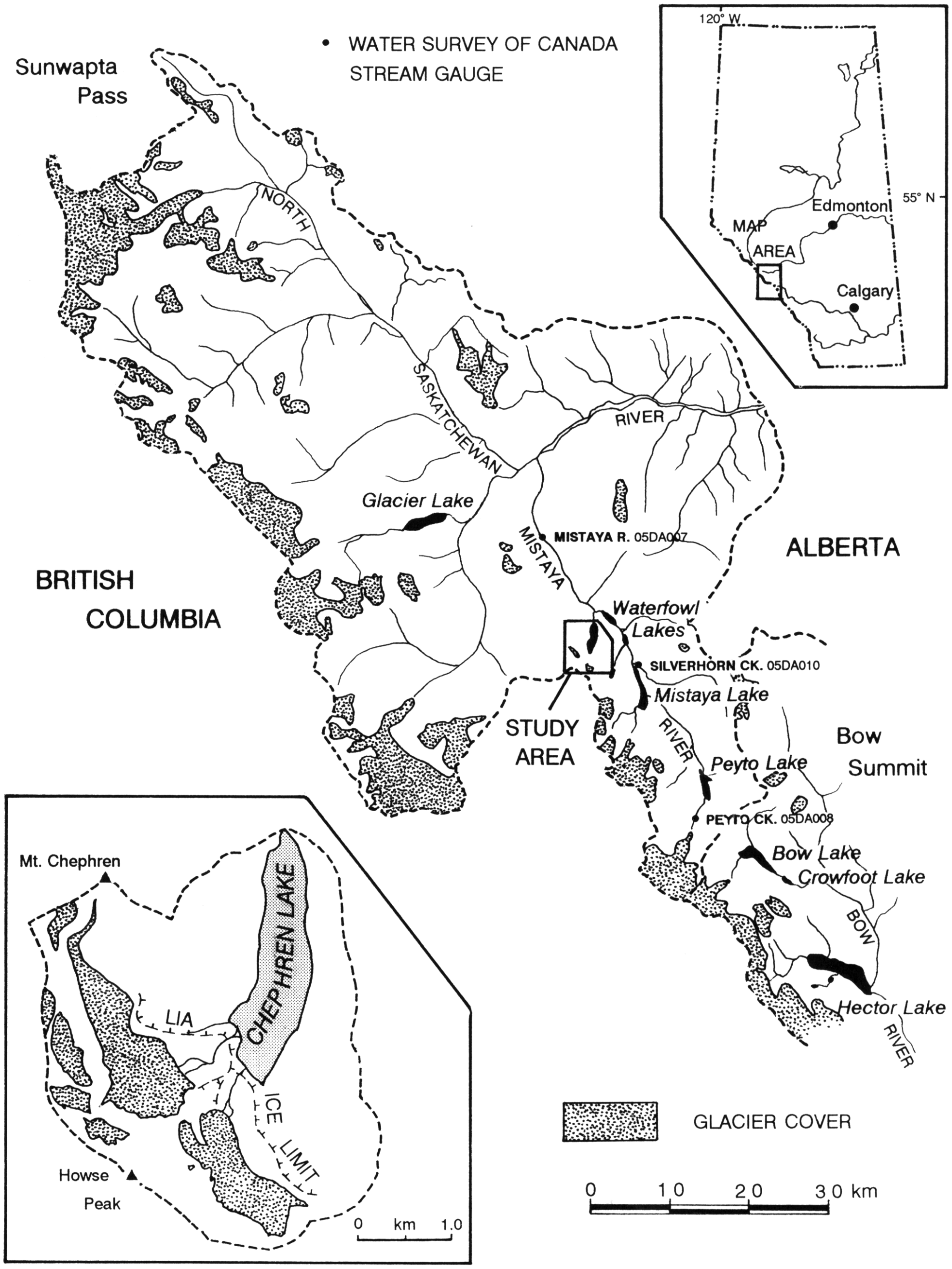

FIGURE 1. Location of the study area and other lake study sites in the headwaters of the North Saskatchewan and Bow river basins, Alberta. LIA = Little Ice Age.

Localisation du site à l'étude et d'autres sites lacustres à la tête des bassins des rivières North Saskatchewan et Bow, en Alberta (LIA : Petit Âge glaciaire).

of the top 3-8 cm of sediment. The bulk samples were analysed for grain size by wet sieving and standard hydrometer/sedimentation cylinder methods. In the latter case, 40 g samples were monitored for 24 hours. Carbonate and organic matter content were determined using loss on ignition (LOI) techniques (*cf.* Dean, 1974).

A 4.3 metre core was obtained from the main lake basin using a portable, light-weight percussion corer (7 cm diameter), built following the design of Reasoner (1993). The coring site was located in the deep distal portion of the lake (Fig. 3) where sedimentation rates were expected to be moderate and dominated by settling of fine materials from suspension. Since coring was conducted from the frozen lake surface in March, 1993, the core was allowed to freeze, then sectioned and split using a diamond saw before shipping to University of Toronto laboratories. Due largely to core catcher design, the sediment column was consistently smeared or down-warped towards the edges. Therefore depth and thickness measurements were made near the centre-line of the core where sediment disturbance was minimized. Comparison of core length and depth of penetration indicate shortening of approximately 5%.

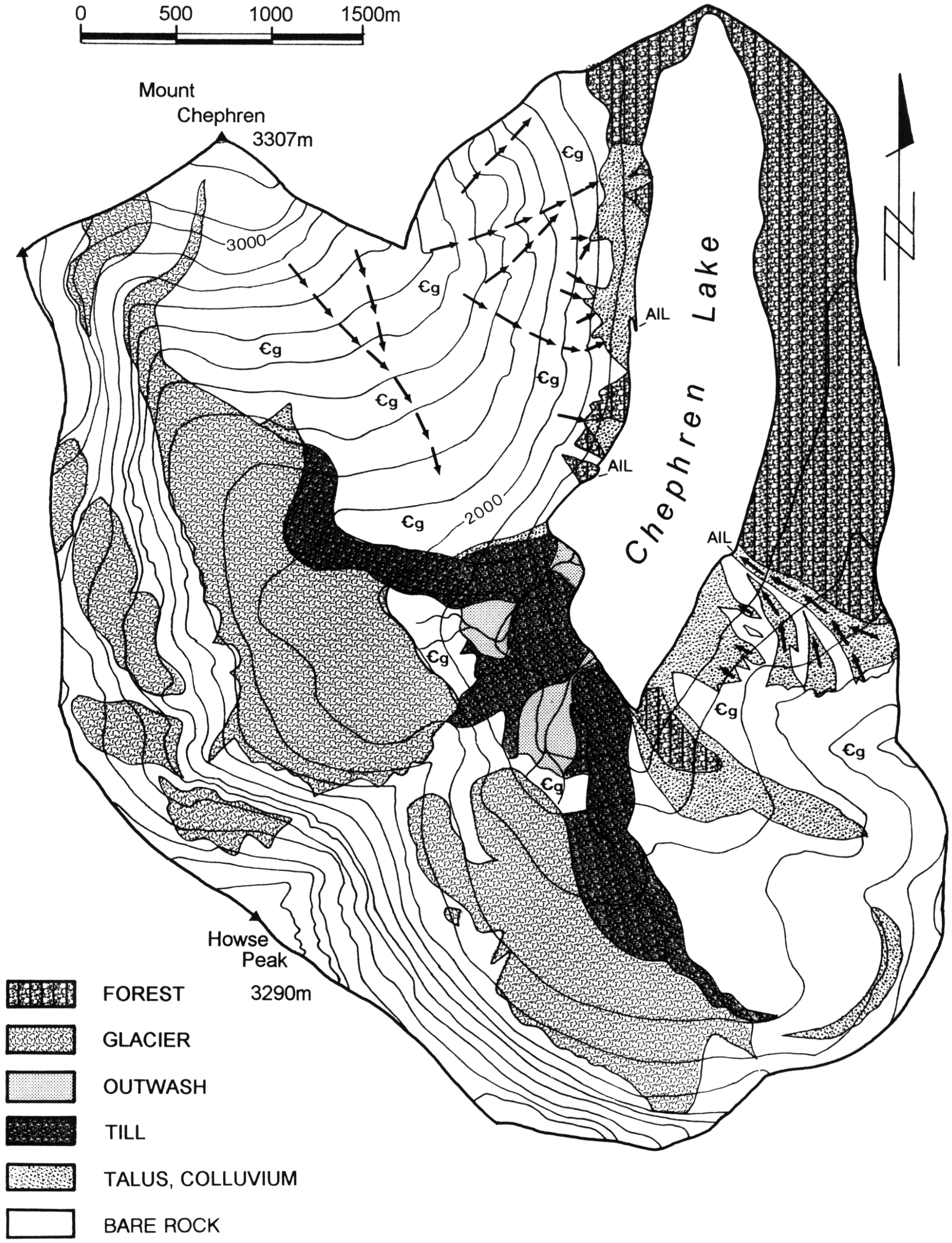

FIGURE 2. Physiography and surface cover of the Chephren Lake basin (based on NTS 1:50,000 Mapsheet 82N/15, NAPL air-photos A20301-88/89 and field mapping). Contour interval is 100 m. Symbol Cg shows approximate extent of lower Cambrian quartzite bedrock; remaining areas are underlain by middle to upper Cambrian carbonates and shales. Arrows indicate prominant debris and avalanche tracks. AIL = avalanche impact landform.

Physiographie et surface couverte par le bassin du Chephren Lake (à partir de la carte 82N/15 à 1/50 000, les photographies aériennes A20301-88/89 et de la cartographie du terrain). L'intervalle entre les courbes de niveau est de 100 m. Le symbole Cg montre l'extension approximative du substratum de quartzite du Cambrien inférieur ; le reste de la région est sur substrat de carbonates et de shistes du Cambrien moyen et supérieur. Les flèches identifient les plus importants couloirs de débris et d'avalanches.

Sections of the core were allowed to thaw and the stratigraphy was logged. Sampling was done at 10 cm intervals in the interior section of the core for geochemical analysis and bulk density and grain size determination. Organic carbon content was determined in this case from <1 g samples (~1 cm^3) using an oxidation-digestion procedure (Allison, 1965). Percent weights obtained using this index are typically 50% of those obtained using LOI (Dean, 1974). Carbonate content was again estimated from LOI with samples of about 10 g. Since the material was dominantly fine textured, 10 g samples were also used for hydrometer analysis spanning a 72 hour period. Finally, large particles not associated with specific laminations were enumerated under a dissecting microscope.

RESULTS

MODERN SEDIMENT DISTRIBUTION

The bathymetry of Chephren Lake reflects the topography of the surrounding basin with an elongate planform, relatively steep side-slopes and a gradual rise towards the distal end (Fig. 3). The lake is partially divided into proximal and main sub-basins by a shallow, lobate rise extending outward from the southwest quadrant of the lake near the western-

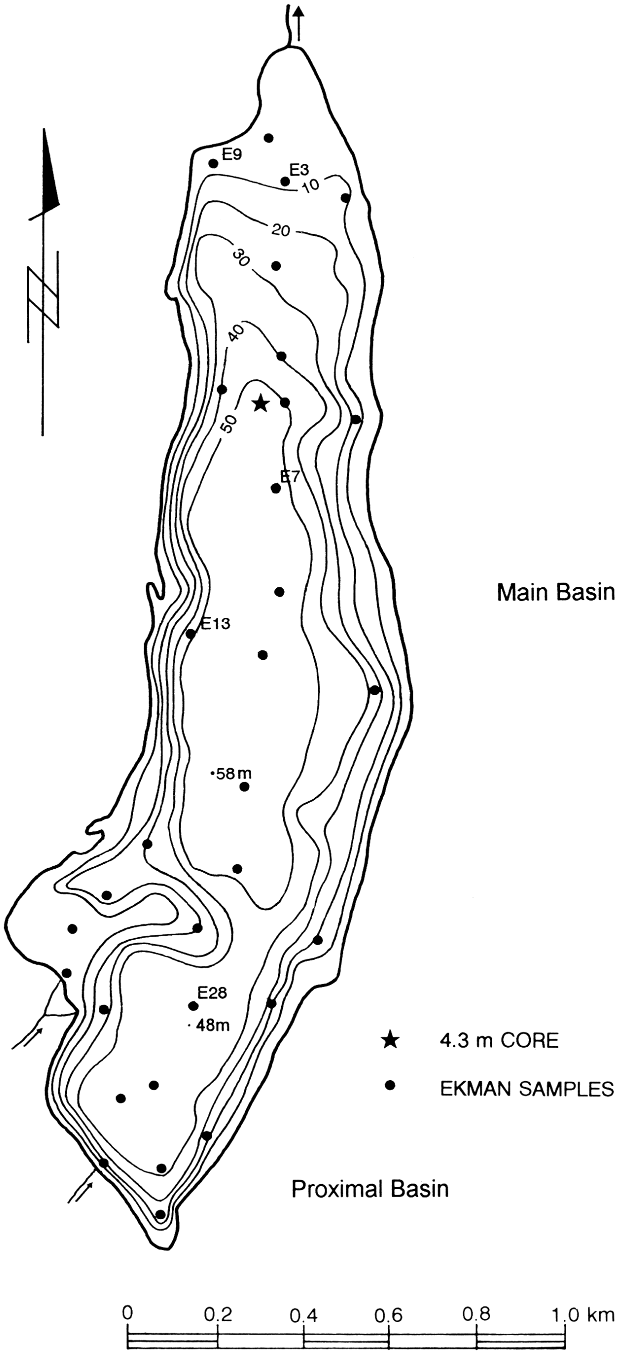

FIGURE 3. Sample locations and bathymetry of Chephren Lake. Isobaths are in metres.

Localisation des échantillons et bathymétrie du Chephren Lake. Les isobathes sont en mètres.

most inflowing stream. This feature is probably a structural bench similar to those in the forefield described earlier but modified by deltaic sedimentation. Both of the sub-basins are relatively flat with a maximum depth of 58 m recorded near the centre of the lake.

The thirty-one Ekman samples show the expected down-lake fining of the sediment from coarse silt to clay (median size changes from 3ø to 9ø) with a concomitant decrease in carbonate (from 25% to 8%) and increase in organic matter (from 1% to 5%) content (*cf.* Smith, 1981; Fig. 4). Eastward cross-lake coarsening and increasing carbonate content reflect right-hand dispersal of sediment due to the Coriolis effect and probably due to deflection by the structural rise. This, and the fact that sediments in the main basin of the lake are dominantly fine grained (average: 2% fine sand, 30% silt, 68% clay) with faint laminations, indicates that settling from suspension is the dominant depositional process (Fig. 5). Normally graded layers of sand (17%) and silt (60%) up to 10 mm thick (E28) are currently restricted to the proximal basin and demonstrate the importance of underflows and associated turbidity currents (Fig. 5a). It is probable that the cross-lake rise is a significant barrier to bottom sediment dispersal and that accumulation in the proximal basin is higher than elsewhere.

Some of the sediments taken from the western and distal portions of the main basin contain isolated angular granules and pebbles (*e.g.* E3, E9, E13; Fig. 5). Lithology of these particles is mixed but includes abundant Gog quartzite. Unlike the finer and better sorted materials entering the lake via the main meltwater streams, size, shape, lithology and position indicate that this material originates on the quartzite slopes overlooking the west side of the lake. Footslopes adjacent to the lake are characterized by a coarse talus apron with more prominant fans located below deep debris/avalanche tracks carved into Gog bedrock (Fig. 2). This debris accumulation is greatest along the northwestern shore of the lake below the scarp face of Mount Chephren. Mid-lake, a characteristic arcuate mound and pool landform similar to those described by Smith *et al.* (1994), indicates recurrent snow avalanche activity.

LONG-TERM LACUSTRINE RECORD

The 4.3 m core was taken from the main lake basin in the vicinity of faintly laminated surface sediments (Figs. 3 and 5). Most of the core (to 326 cm depth) consists of laminated silty clays, interbedded with occasional sand/silt laminae or beds that are one grain diameter (sand to pebbles) in thickness (Fig. 6). This upper section can be described in terms of three facies: 1) laminated silts and clays, 2) discrete sand or silt laminae, and 3) coarse particle beds. The latter two facies are most common in the lower part of the sequence and account for approximately 3 % of its total length. At 220 cm depth there is a 16 mm thick accumulation of Bridge River tephra. Identification of the ash is based on petrographic and electron microprobe analysis of the sample (Dirszowsky, 1994) and the stratigraphic significance is outlined below. The lower section of the core (below 326 cm) consists of three thick (>12 cm) beds each grading crudely upward from gravel to clay.

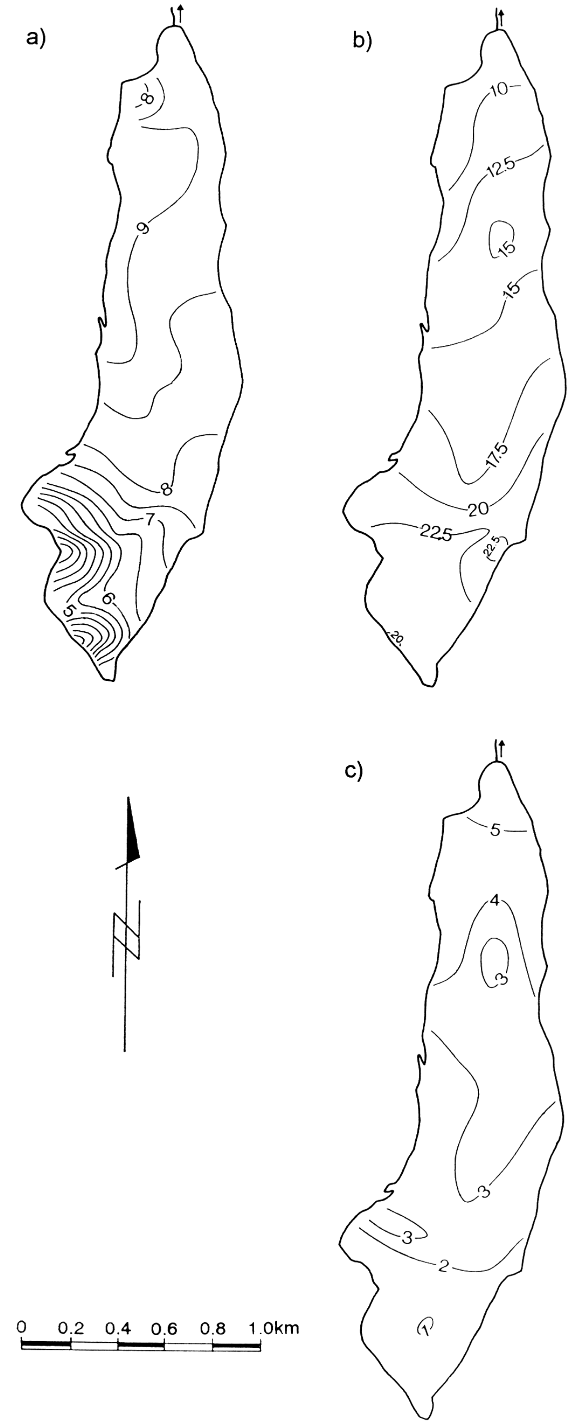

FIGURE 4. Distribution of bottom sediment characteristics in Chephren Lake: a) median grain size (ø) excluding isolated particles greater than sand size; b) carbonate content (% wt. LOI); c) organic matter content (% wt. LOI).

Caractéristiques de la répartition des sédiments de fond au Chephren Lake : a) granulométrie moyenne (ø), excluant les particules isolées de taille plus grosse que celle des sables ; b) la teneur en carbonates (% du poids à la PAF) ; c) teneur en matière organique (% du poids à la PAF).

Laminated Silts and Clays

This facies consists of 67% to 81% clay by weight, while sand never exceeds 1%. Median grain sizes range from 9.0ϕ (1.9 µm) to approximately 10.5ϕ (0.7 µm). Colour of the material while moist is olive-grey (5Y 4/2-7/2) with occasional light grey (2.5Y 6.5/0) bands. About 75% of the material is faintly laminated, but it varies, sometimes abruptly, from distinctly laminated to massive. Faint laminations are distinguished by tonal variations, and with few exceptions, the boundaries between them are gradational. Thus distinction of individual laminae based on grain size is not possible everywhere in the core.

The more distinctly laminated sediments of the lacustrine sequence resemble classical varves (*cf.* Ashley, 1995), with light laminae grading into dark laminae to produce rhythmic couplets. Inspection of the core under magnification confirms that light and dark half-couplets correspond to relatively coarse and fine sediment respectively. Bulk grain size analysis of both faintly and distinctly laminated sediment reveals bimodal distributions (7.5ϕ - 8.5ϕ and 9.5ϕ - 10.0ϕ) in most cases (Table I). The bimodality reflects coarser and finer sub-populations of the lighter and darker sediments. Most couplets are less than 3.5 mm in thickness, although exceptionally thick ones (up to 10 mm) are present between 203 cm and 211 cm. Contacts between couplets are generally sharp with occasional waviness possibly due to loading of coarser material onto fine. Rhythmic couplets are grouped into sequences of up to 95 successive units (Table I; Fig. 6). Most of these series begin and end abruptly; however, some gradually thin and blend with the faintly laminated material. Most of the couplets within series vary little in thickness (Table I). The thickness ratio of fine (dark) to coarse (light) half-couplets is typically 1:1, with the coarser being the more variable.

Massive sediments in the core are rare. The top several cm of the core appear massive, but it is likely that the high water content at the surface led to disturbance during core retrieval. In the vicinity of the coring site Ekman samples exhibit the same faint lamination found lower in the long core (Fig. 5b). In the modern sediments, massive structures are found only in the distal and shallow sections of the lake where turbidity currents are unable to affect them (cf. Desloges and Gilbert, 1995).

Silt and Sand Laminae,

This facies consists mainly of discrete fine to medium sand layers, but may also include coarse silt layers which contrast well with the surrounding silts and clays (Fig. 6). The layers are up to 13 mm in thickness but average less than 2 mm. Most are well-sorted and all possess sharp upper and lower contacts. Normal upward grading is apparent in thicker examples. Many of the better sorted silt and sand laminae are found in combination with rhythmic couplets, and seven of the thicker examples are located between coarse and fine half couplets. Most well sorted examples of this facies posses a grey limestone-shale lithology indicative of basin headwater sources. However between 192 and 228 cm depth, sand layers are relatively coarse, thick, less well sorted, and possess a distinctive, reddish-yellow quartzite lithology which corresponds to material found on slopes immediately adjacent to the coring site.

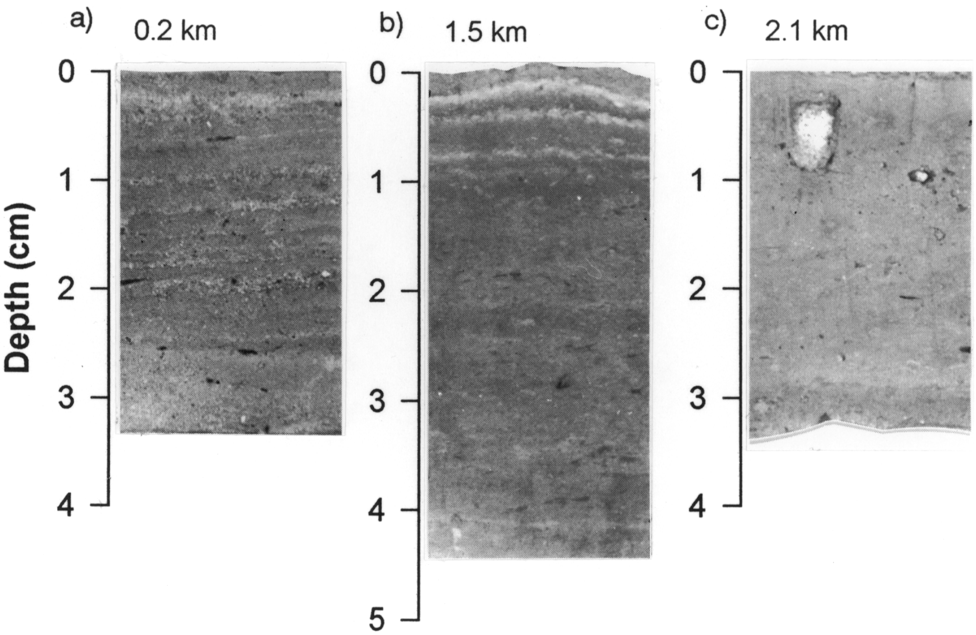

FIGURE 5. Comparison of Ekman samples: a) graded sand and silt, E28; b) faintly laminated sediment, E7; c) nearly massive sediment with isolated clasts, E3. Distances indicated are from inlet streams at south end of the lake.

Comparaison des échantillons d'Ekman : a) sable et limon classés, E-28 ; b) sédiment faiblement laminé, E-7 ; c) sédiment presque massif avec des débris isolés, E-3. Les distances signalées sont calculées à partir de ruisseaux qui se jettent à l'extrémité sud du lac.

TABLE I

Location and character of rhythmic couplets

Depth (cm)	No. of couplets	Total thickness (mm)	Avg. couplet thickness (mm)	Grain size distribution	Sequence style
26-27	6	6	1.0	unsampled	abrupt
38-43	53	64	1.2	unsampled	starts abruptly, thinning and fading upward, preceded by sporadic couplets from 50 cm
108-128	54	96	1.8	weakly bimodal	starts abruptly, thinning and fading upward, coarse/fine ratio decreases upward, interbedded with sand laminae
“	30	68	2.3		
“	11	35	3.2		
151-153	11	20	1.8 (up to 3.5)	bimodal	abrupt, coarse/fine ratio decreases upward
196-211	23	80	3.5	bimodal	ends abruptly, lower section has diffuse boundaries, preceded by isolated couplets and sand/particle laminae from 226 cm
“	9	70	7.8		
226-228	14	32	2.3	unsampled	abrupt, coarse/fine ratio high, preceded by isolated couplets and sand/particle laminae from 236 cm
245-252	40	70	1.8	unsampled	ends abruptly, preceded by single couplets and sand/particle laminae from 261cm
261-265	22	40	1.8	bimodal	abrupt
266-276	15	20	1.3	bimodal	discontinuous sequence interbedded with particle laminae and faintly laminated silt/clay
285-290	27	50	1.9	unsampled	abrupt, preceded by 9 isolated groups of up to 5 couplets from 322 cm
322-326	20	40	2.0	uniform	abrupt, coarse/fine ratio high

Coarse Particle Beds

This facies, consists of poorly sorted, thin (as little as one grain diameter) layers, and isolated angular clasts up to several centimetres in diameter. Lithology varies from layer to layer (dark grey shale or limestone, or grey or brown quartzite), but is generally uniform within layers. As in the case of the surficial sediments along the west side of the lake, large clast sizes, poor sorting and angular shape all suggest that the material is derived from the slopes of Mount Chephren. Limestones and shales would then be derived from the higher elevations. This facies is found entirely below 159 cm depth in the long core but is similar in appearance to materials found in lake bottom samples obtained closer to shore. The facies is often associated with, but not confined to, rhythmically laminated silt and clay segments in the core.

Basal Diamict

The lower-most metre of the core consists of three crudely sorted beds, each bed grading sharply upward from a clast-rich clay base (clasts, 15-20%; sand, 7-9%; silt, 9-12%; clay, 64-67%) to massive sand- and clast-free silts and clays above (clay, 76-87%). Clays are generally finer (*i.e.* beyond the limit of accurate hydrometer analysis) than in the facies of the lacustrine sequence. Basal clasts have mixed lithologies, are angular and up to 8.5 cm in length (long axis). The lower contacts of the two upper beds are abrupt, but marked by approximately 5 mm of horizontally "streaked" fine material. The base of the lowest bed was disturbed by coring.

Long-term rates of sediment accumulation were estimated using radiocarbon dated macrofossils (conifer parts) found in the core at 153 cm (1780 ± 60 yrs BP, TO-4040) and 320 cm (4030 ±70 yrs BP, TO-4303) and the Bridge River tephra layer at 220 cm. Table II indicates linearly interpolated accumulation rates based on the uncorrected ^{14}C dates and on calendar dates determined using the dendro-calibration curves and methodology of Stuiver and Reimer (1993). While this method accounts for possible variations in atmospheric ^{14}C, the error range is increased due to uncertainty in the lab determination (counting error) and in the calibration curve. In the case of the Bridge River tephra, calibration is based on the average radiocarbon age (2435 ± 26 yrs BP) of the outer rings of six tree specimens used to date the original eruption less 15 years to account for the use of multiple rings (Clague *et al.*, 1995). The error term (± 26 yrs) quoted for the Bridge River tephra is two standard deviations; however, the majority of the error in the calibrated age of the tephra is due to atmospheric ^{14}C variability. The calendar age could therefore range over 350 years (*cf.* Leonard, 1995.

A second possible source of error in the accumulation rate determinations stems from core disturbance and post-depositional sediment compaction, either of which could render linear interpolation inappropriate. Of particular concern is the strong density gradient usually associated with sediments not yet subject to great overburden pressure. The limited shortening observed in the Chephren core may be caused by ploughing of sediments ahead of the corer as well as by compaction. Some workers argue that the degree of compaction will increase with depth as the core barrel

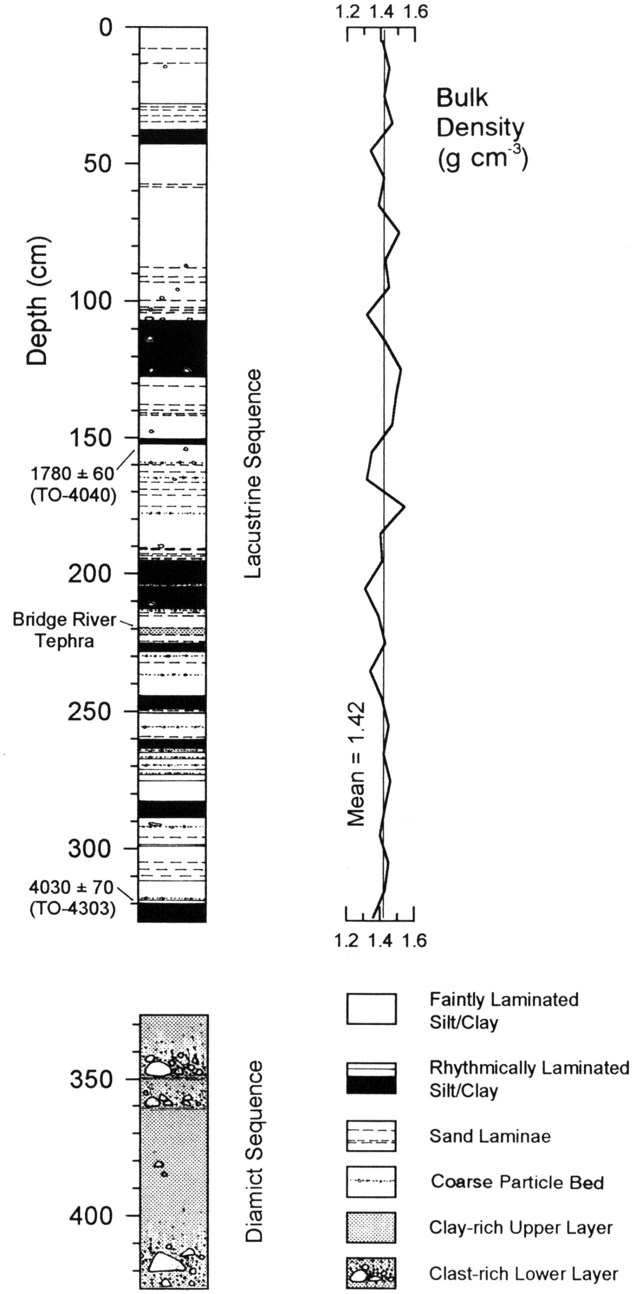

FIGURE 6. Stratigraphy and bulk density of the 4.3 m core taken from the distal end of the main basin. Except within rhythmically laminated sequences (black), horizontal lines represent only the most prominent (> 0.5 mm thick) examples of each facies.

Stratigraphie et densité apparente de la carotte de 4,3 m provenant de l'extrémité distale du bassin principal. Sauf à l'intérieur des séquences laminées (en noir), les lignes horizontales ne représentent que les parties les plus accusées (> 0,5 mm d'épaisseur) de chacun des faciès.

encounters greater resistance from relatively stiff sediment (Cumming *et al.*, 1993). It has also been argued that compaction will be greater in the most porous (least consolidated) sediments, assuming that pore water is able to escape during corer penetration (Crusius and Anderson, 1993). In the latter case core compaction can compensate for depositional compaction (Desloges and Gilbert, 1994). In the Chephren Lake core, pore water expulsion is indicated by disturbance of the upper few cm of core. Furthermore no significant down-core trend in bulk density is evident (Fig. 6) indicating that sediments are uniformly compacted throughout and that linear interpolation is reasonable in this case. Small variations in bulk-density are due to actual changes in grain-size.

TABLE II

Dates and accumulation rates from Chephren Lake

Depth (cm)	Material dated	Lab No.	Age (Yrs BP)	Uncorrected accumulation rates (mm a^{-1})	Calendar dates (2σ)	Corrected accumulation rates (mm a^{-1})
				0.86 (0.83-0.89)‡		0.90 (0.82-0.97)§
153	gymnosperm twig	TO-4040	1780 ± 60*		120 A.D.- 415 A.D.	
				1.05 (0.92-1.21)		0.93 (0.57 - 1.29)
220	B.R. tephra		2420 ±26†		755 B.C. - 400 B.C.	
				0.62 (0.59-0.66)		0.52 (0.43 - 0.61)
320	gymnosperm twig	TO-4303	4030 ±70*		2700 B.C. - 2395 B.C.	

* IsoTrace, University of Toronto, uncalibrated radiocarbon dates (1σ error term); † mean uncalibrated radiocarbon date from Clague *et al.* (1995) based on multiple tree specimens and corrected for tree ring position (2σ error term); ‡ range results from error term; § range based on maximum and minimum calendar dates.

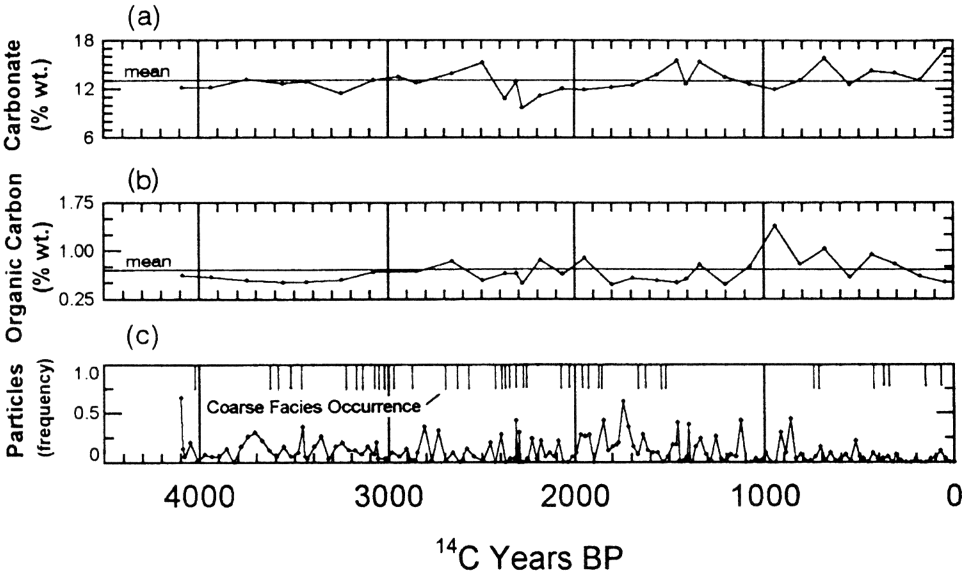

FIGURE 7. Geochemical indicators of the Chephren Lake core: a) carbonate content based on LOI; b) organic carbon content; c) relative frequency of countable particles disseminated in silt/clays, and the occurrence of sand laminae and coarse particle beds described in text and in Figure 6. Dates are based on linear interpolation between radiocarbon dates and Bridge River tephra. Age-depth relations are adjusted using elevated annual (varve) depositional rates in rhythmic sections and assumed constant rates between sections. These time adjustments change the chronology by only a few decades in comparison with simple linear interpolations between ^{14}C dates.

Les indicateurs géochimiques contenus dans la carotte du Chephren Lake : teneur en carbonate en fonction de la PAF ; b) teneur en charbon organique ; c) fréquence relative des particules dénombrables disséminées dans l'argile ou le silt ainsi que la présence de feuillets de sable et de couches de particules grossières (voir texte et fig. 6). Les dates sont fondées sur une interpolation linéaire entre les dates au radiocarbone et le téphra de Bridge River. Les relations âge/profondeur sont établies en fonction du taux de sédimentation annuel élevé des varves dans les sections de rythmites, ce taux étant présumé invariable entre les sections. Ces réglages temporels ne modifient la chronologie que de quelques décennies comparativement aux interpolations linéaires simples entre les datations au ^{14}*C.*

DOWN-CORE GEOCHEMICAL VARIATIONS

In the Chephren Lake sediments the apparently increased accumulation rates in the upper core are accompanied by generally above average carbonate content (Fig. 7a). Organic carbon content is variable but with elevated concentrations between 75 and 85 cm depth and between 160 and 170 cm depth. Using linear interpolation, these depths correspond to dates of 1100-800 BP and 2200-1900 BP respectively (Fig. 7b). Of considerable note is the consistent decline over the last 1000 years. Particle counts, the occurrence of the coarse facies and variations in clast lithology in the Chephren Lake core provide possible complementary evidence of long-term Neoglacial environmental change (Fig. 7c). Throughout the core, sand and clast frequency is subject to high frequency fluctuations, but overall the number of particles deposited appears to have decreased. Sand laminae are much rarer while clast beds are completely lacking, above 159 cm depth (after *ca.* 1850 BP).

DISCUSSION

INTERPRETATION OF FACIES

The rhythmic lamination is evidence of seasonally variable deposition. Summer turbidity currents may alternate with winter settling from suspension (Ashley, 1995), or summer and winter settling from suspension may be separated by autumn overturn of the lake (Sturm and Matter, 1978). While turbidity currents are not necessary for the formation of varves, they do provide pulses of coarser sediment that make varves more recognizable. The similarity in bimodal size distributions of the faintly and distinctly laminated sediments suggests that the two groups are genetically related. The transition to poorer definition of the couplets might be expected if overall sedimentation rates become very low and the sediments particularly fine. In this case the occurrence of distinct rhythmic sedimentation in Chephren Lake (Fig. 8a) indicates an increased influx of sediment and, possibly the establishment of more distinct, seasonal changes in hydrology or lake temperature regime. We suggest that, in some cases at least, the rhythmically laminated portions of the core sequence record the release of fine subglacial material because of significant ice ablation and glacier retreat, probably related to increased summer temperatures (*cf.* Desloges, 1994; Lemmen *et al.*, 1988). The duration of the longest rhythmite sequence recorded here (beginning

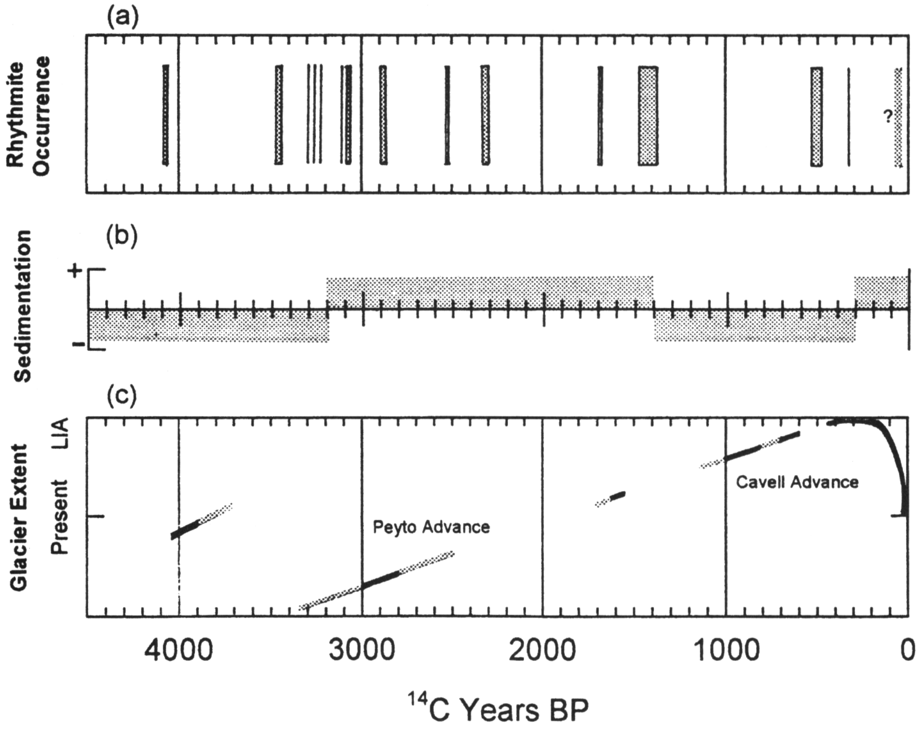

FIGURE 8. Indicators of Neoglacial chronology in Chephren Lake and region: a) occurrence of rhythmites in the core (the most recent occurrence is inferred). Dates are based on linear interpolation between radiocarbon dates and Bridge River tephra as in Fig. 7; b) periods of above and below average sedimentation in Hector Lake (after Leonard , 1997); c) regional glacier chronology (advance phases) based on diagram in Luckman *et al.* (1993). Solid lines match the original diagram and indicate greater confidence. The lines have been extended (stippled portions) to include the full range of ^{14}C dates quoted in the original text. The last 700 years is based on dendrochronology rather than radiocarbon dating.

Les indicateurs de la chronologie néoglaciaire au Chephren lakes et dans la région : a) la présence de rythmites dans la carotte (la plus récente étant présumée). Les dates sont fondées sur l'interpolation linéaire entre les dates au radiocarbone et le téphra de Bridge River (comme à la fig. 7) ; b) périodes de sédimentation au-dessus et en dessous de la moyenne dans le Hector Lake (d'après Leonard, 1997) ; c) chronologie glaciaire régionale (phases d'avancée) fondée sur le diagramme de Luckman et al. (1993). Les lignes pleines coïncident avec le diagramme original et reflètent un bon degré de confiance. Les lignes ont été prolongées (trames) afin d'inclure toutes les dates au ^{14}C signalées dans le texte original. Les 700 dernières années ont été déterminées par dendrochnologie plutôt que par radiotadation.

ca. 1460 BP based on uniform long-term accumulation rates), is about 95 years (Table I). Most of the rhythmic segments represent less than 30 years of deposition, and begin and end abruptly. This response is reasonable for relatively small cirque glaciers which respond quickly to temperature and precipitation changes (*cf*. Lawby *et al*.,1995).

Non-rhythmic sand and silt laminae found both in proximal surface sediments and occasionally at depth in the long core are considered to be the product of underflow currents (*cf*. Smith, 1978; Sturm and Matter, 1978). Most of those in Chephren Lake are not graded or are too thin to show grading, but are well sorted and possess uniform, grey (limestone and shale) lithology. It appears that most of those found in the core originated at the head of the lake, and correspond to particularly energetic inflow events. The arrangement of many of the laminae between coarse and fine half-couplets suggests that the responsible currents were related to large, late summer inflows. Enhanced glacier melt or heavy rains are possible triggering mechanisms. The dominantly quartzite sand layers found between 192 and 228 cm depth are less well sorted, and are thought to represent localized turbidity currents generated from failures on slopes adjacent to the coring site.

Coarse particle beds and isolated clasts, both in the modern sediments and at depth in the core, are associated with slopes overlooking the west side of the lake. Morphology of these slopes indicates they are subject to occasional failure (debris flow, rock avalanche) and recurrent avalanche processes. Since poor sorting of the beds and the presence of isolated clasts indicates relatively direct deposition, we believe that slope material is transported to the lake bottom mostly via avalanching onto lake ice in winter with some redistribution during spring break-up (*cf*. Weirich, 1985). Reworking of shore material by lake ice is also possible, but would be limited by the bouldery nature of the material.

The three beds of the basal diamict exhibit features ascribed by Middleton and Hampton (1976) to sediment gravity flows, but the exact type is not clear from the limited cross-section. The mixture of large clasts with clay suggests subaqueous debris flow; however, the grading is indicative of turbidity current deposition, and/or the "dilution" of moving sediment with lake water and consequent settling of the clasts. Given the large size and angular shape of the basal clasts, it is likely that slope failure near the site triggered subaqueous debris flows or slides which then crossed and entrained slope and bottom lacustrine sediments. Turbulence created by the initial movement may have suspended the finer material and initiated a turbidity current. The sequence represents successive accretion of three flow events, possibly occurring within a relatively short period.

VARIATIONS IN CARBONATE AND ORGANIC CARBON

Intervals of above average carbonate and below average organic carbon, particularly between 1800 and 1100 BP and after 900 BP (Fig. 7), are consistent with the idea that glacier expansion across largely carbonate terrain in the Chephren headwaters would produce a greater flux of glacier-derived clastic material. Leonard (1986) and Souch (1994) related higher organic matter content to a decrease in clastic sediment input and possibly higher autochtonous organic production under ameliorated lake and climate conditions. The above interpretations are supported by the observed down-lake depletion of carbonate and ennrichment of organic matter in the modern Chephren Lake sediment away from the cold water and mineral inputs of contemporary glaciers.

ACCUMULATION CHRONOLOGY

Overall accumulation rates in Chephren Lake appear to have increased at least after *ca*. 2420 BP. Assuming no differential compaction, Table II indicates that the long-term accumulation rate of 0.5 mm a^{-1} prior to deposition of the Bridge River tephra was about half that in the two later intervals. These results are comparable to those for nearby Crowfoot, Bow and Hector lakes (Leonard, 1986, 1997), and Lake O'Hara and Opabin Lake (Reasoner and Rutter, 1988). In the latter two lakes, increased accumulation rates are noted following the deposition of the Bridge River tephra. In Crowfoot, Bow and Hector lakes, accumulation rates first increased after *ca*. 4000 BP and then again during the last millennium. The increases are assumed to correspond to deteriorating climatic conditions, increased ice extent and thus greater sediment production.

Accumulation rates, particularly after 2420 BP are comparable to the minimum thicknesses of the rhythmic couplets assuming that these represent varves (˜1.0 mm a^{-1}; Table I). In the earliest and latest intervals, maximum annual accumulation based on couplet thickness was 4-5 times the average, while during the intermediate interval, exceptionally thick rhythmites imply annual accumulation rates as much as 11 times the average. This magnitude of short-term variation in sedimentation has been widely noted in other glacier-fed lakes (*e.g*. Sturm and Matter, 1978; Smith, 1981; Østrem and Olsen, 1987) reflecting inter-annual changes in basin hydrology.

Leonard (1997) has established a varve chronology for nearby Hector Lake (Fig. 1) which spans the last 4500 years (Fig. 8b). In their original record, periods of distinctly elevated sediment accumulation occur for intervals of between 20 and 100 years and are comparable in length to the sequences of well laminated sediment noted for the Chephren Lake core. Given the lack of detailed chronologic control at Chephren Lake, it is not yet possible to make precise comparisons of these moderate to high frequency fluctuations. However, there is general correspondence between the more continuous intervals of weakly laminated sediments in Chephren Lake (*i.e*. prior to about 3450 BP and between 1350 and 650 BP; Fig.8a) and below average sedimentation in Hector Lake which suggests synchronous reductions in sediment yield.

The short-lived glacier fluctuations represented by the sequences of rhythmite formation in Chephren Lake can also be compared with a chronology of regional glacier advances (Fig. 8c; *cf*. Luckman *et al*., 1993). The earliest evidence for increased Neoglacial activity in the Canadian

Rockies comes from Boundary Glacier (Gardner and Jones, 1985) where an overridden tree stump suggests a starting date between about 4100 and 3800 BP. Detrital wood and overridden *in situ* stumps, recovered from the forefields of Peyto, Robson, Yoho and Saskatchewan glaciers indicate advancing glaciers at *ca*. 3300-2500 BP (Peyto Advance; Luckman *et al*., 1993) and 1700-1500 BP. Estimated inception of the Little Ice Age or Cavell Advance (Luckman and Osborn, 1979) has been revised from 400 BP to at least 900 BP based on discoveries at Robson Glacier (Luckman, 1995; Osborn and Luckman, 1988). There is little evidence of glacier advance between *ca*. 600 and 450 BP. It is apparent in Figure 8 that most rhythmite sections approximately bracket known regional phases of glacier advance. Most prominent examples (*i.e*. greater than 25 rhythmites) occur immediately following advance phases at *ca*. 3460 (follows "Boundary" advance), 2330 (follows Peyto Advance), 1470 (follows unnamed advance) and 530 (follows Cavell Advance) BP. One prominent sequence (27 rhythmites) falls within bracketing dates for the Peyto Advance, at *ca*. 2900 BP. The Peyto Advance was inferred from numerous detrital wood dates between 3000 and 2800 BP and relatively few beyond that range (*e.g*. one date of 2490 BP). While not all of the short abrupt rhythmite sequences necessarily indicate glacier retreat, they suggest that the Peyto advance may have been characterized by several short-term fluctuations.

Moraine dates, combined with the uniform spacing of recessional moraines in the glacier forefields of the Chephren basin show that ice retreat from the Little Ice Age maximum was continuous and probably rapid. Glacier fronts were close to present positions by at least 1920 A.D. with the main phase of glacier retreat occurring between then and 1880 A.D. Based on patterns deeper in the core, this should correspond to rhythmic sedimentation at depths of around 6 to 10 cm in the Chephren Lake sediments assuming average accumulation rates of 0.9 mm a^{-1} (Table II). Such lamination is not evident in the long core, possibly due to disturbance during core retrieval. The probable depth is beyond that of the short cores. Greatly increased rates of sediment accumulation between 1850 and 1920 A.D. are, however, a prominent feature of the Hector Lake varve chronology (Leonard, 1997) reflecting glacier retreat from Little Ice Age maxima at that locality. The consistently decreasing rates of organic carbon in sediments after 900 BP coupled with increasing carbonate content remain the strongest evidence for increased clastic input over the Little Ice Age interval at Chephren Lake.

The lithology, size and sedimentary structure of the coarse particle beds and some examples of the sand laminae indicate that inputs from adjacent hillslopes are important components of the Chephren record. Large scale failures (*e.g*. rock avalanches) along the lake margin likely promote development of turbidity currents and may produce a lake wide coarsening of sediment in some cases. Snow avalanches or debris flows generated on specific slopes affect lake sediments more locally and are capable of introducing coarse clastic material. The Chephren core records some of these events but assigning precise environmental conditions that lead to their formation remains problematic. Grove (1972) and Souch (1989) have suggested that short- and long-term decreases in slope stability correspond to cool wet conditions. An abundance of readily transported weathered material also was used by Souch (1989) to explain part of the increase in sediment flux during the Neoglacial in a small, low energy (non-glaciated) basin in the Coast Mountains of British Columbia. Our record shows that deposition of locally derived slope material in the form of poorly sorted coarse material was significantly more frequent and more widespread (*i.e*. reaching the centre of the lake) early in the Neoglacial. This may be related to the presence of "relict" slope forms (talus, impact landforms) at the foot of Mount Chephren where lichen cover is higher and some soil development has occurred. The presence of locally derived sediment gravity flow deposits at the base of the core precludes the precise dating of the onset of the Neoglacial, but is itself diagnostic of elevated levels of early Neoglacial mass wasting. This points to the possibility of unstable slopes, high sediment availability and deteriorating environmental conditions just prior to *ca.* 4030 BP.

SUMMARY AND CONCLUSIONS

Glaciolacustrine depositional processes have dominated sedimentation in the distal part of Chephren Lake during most of the Neoglacial period. Distinct sequences of rhythmic laminae, many of which begin and end abruptly, relate to periods of higher sediment input and probably greater seasonal contrasts in runoff and lake stratification. These conditions are thought to relate to early phases of glacier retreat as climate ameliorates and sub- and proglacial sediments are flushed from the system. The small size of the Chephren glaciers and their dependency on inputs of snow from the cirque headwall, make them particularly sensitive to short term changes in precipitation and temperature. When compared to the regional terrestrial record of glacier fluctuations, sequences of rhythmic laminae are most common immediately following periods of known regional glacier advance. In addition, the highest frequency of rhythmites and coarse facies occurs during the interval 3200 to 1400 BP which is coincident with above average rates of sedimentation in nearby Hector Lake. There is insufficient evidence available from the Chephren Lake sediments examined to date to confirm the overall effects of Little Ice Age advance and retreat, but aging of the moraines indicates that the Cavell advance was the most extensive.

Excluding the basal sediment gravity flows, the coarse facies in the Chephren core account for less than 3% (by volume) of the sediments delivered to this site. Non-glacial processes in the form of avalanches, ice rafting, slope failures and associated subaqueous flows generated by these failures are likely responsible for most occurrences of these facies. The largest source of these non-glacial materials is the north and east facing slopes of Mount Chephren, the exposed lower parts of which are dominated by Gog quartzites. Slope instability appears to be highest earlier in the record and then declines. Verification of this trend awaits analysis of a group of lakes where sediments record the changing frequency of slope derived material which span known climate variations over the Neoglacial or entire Holocene (*cf.* Jonasson, 1991).

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