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Reconstructing hydro-climatic events and glacier fluctuations over the past millennium from annually laminated sediments of Cheakamus Lake, southern Coast Mountains, British Columbia, Canada

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Abstract

We recovered sediment cores from Cheakamus Lake in the southern Coast Mountains, southwest British Columbia, to reconstruct late Holocene environmental conditions in the watershed. The cored sediments are inorganic, rhythmically laminated clayey silt. Radiocarbon ages and correlation of lamina thickness with the magnitude of the annual flood recorded at a nearby gauging station indicate that the laminae are varves. We discriminate seven types of varves on the basis of couplet thickness and internal structure, and compare them to annual hydrographs over the period of record. The seven varve types record summer snowmelt floods, autumn floods, mid-season floods, years with two major floods, years with three major floods, years with more than three major floods, and periods of sustained glacier runoff. Varves attributed to autumn storms and glacier runoff are dominant, exhibit serial dependence, and are most common during six periods: AD 1300–1320, 1380–1410, 1470–1500, 1710–1730, 1880–1906, and 1916–1945. In contrast, varves attributed to summer snowmelt floods are randomly distributed through time. Thickest varves occur during the decades AD 1090–1110, 1120–1170, 1210–1250, 1310–1330, 1390–1450, 1720–1780, 1860–1900, and 1920–1945. The relation between Little Ice Age glacier activity and lake sedimentation is complex, but the thickest varves coincide with times of rapid glacier retreat and periods when air temperatures were warmer than average. The results confirm the importance of sediment transfers during the summer and autumn runoff season in the British Columbia Coast Mountains.

1. Introduction

Proxy environmental records that have annual resolution are valuable for assessing natural and human-induced climate change. In the Northern Hemisphere, for example, tree rings and ice core records are widely exploited to reconstruct changes in air temperature and precipitation over the past centuries and millennia. Another high-resolution environmental proxy, which is equally important but less commonly used, is clastic sediments in proglacial lake basins. If sedimentation rates are high and seasonally variable, and if bioturbation rates are low, the sediments may be annually layered (i.e., varved).

Clastic varves can record brief climate events, as well as persistent conditions that control sediment production and delivery to the lake. In western Canada, major flood events (Desloges and Gilbert, 1994; Menounos et al., 2005; Cockburn and Lamoureux, 2007) and anomalously warm and cool periods (Leonard, 1981; Menounos, 2006) have been reconstructed from varved sediments. Changes in ice cover in glacierized basins have been invoked to explain long-term (>100 yr) changes in sedimentation rates (Leonard, 1997; Osborn et al., 2007). However, changes in sediment availability and storage beneath alpine glaciers, and changes in non-glacial sediment sources can complicate the relation between glacier extent and sediment yield (Hallet et al., 1996; Leonard, 1997). Consequently, any relation between ice cover and lake sedimentation for periods shorter than a century is tenuous.

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This paper reports results of an analysis of varved sediments spanning the past 1000 yr, collected from Cheakamus Lake, a large proglacial lake in the southern Coast Mountains of British Columbia. The objectives of the paper are to (1) assess the type and quality of environmental information contained in the sediments and (2) examine the relation between glacier fluctuations and sediment delivery to the lake.

2. Study area

Cheakamus Lake and its watershed (216 km^2) are located in Garibaldi Provincial Park, 70 km north of Vancouver, British Columbia (Fig. 1). The lake occupies a single, elongate basin with a maximum depth of 120 m (Fig. 1). Like other large, oligotrophic lakes in temperate, maritime, montane environments of North America, Cheakamus Lake is dimictic and weakly thermally stratified during summer. It develops a cover of ice in winter.

The Cheakamus River basin is underlain by rocks of the Coast Plutonic Complex, mainly Jurassic quartz diorite and granodiorite, and Cretaceous metamorphosed volcaniclastic rocks of the Gambier Group (Monger and Journeay, 1994). The entire basin was covered by the Cordilleran ice sheet during the local maximum of the last glaciation about 17,000 yr ago (Clague, 1981). Patchy glacial and colluvial deposits occur on slopes, and valley floors contain colluvial fans and aprons and gravelly alluvial deposits.

Relief in the watershed upstream of Cheakamus Lake is about 1800 m. Headwater areas support glaciers, which collectively occupy 23% of basin (Fig. 1). The largest glaciers are Cheakamus, MacBride, Forger, and Ubyssey glaciers, each of which has an area in excess of 4 km^2. Lateral and end moraines lacking mature vegetation delineate the maximum extent of glaciers during the Little

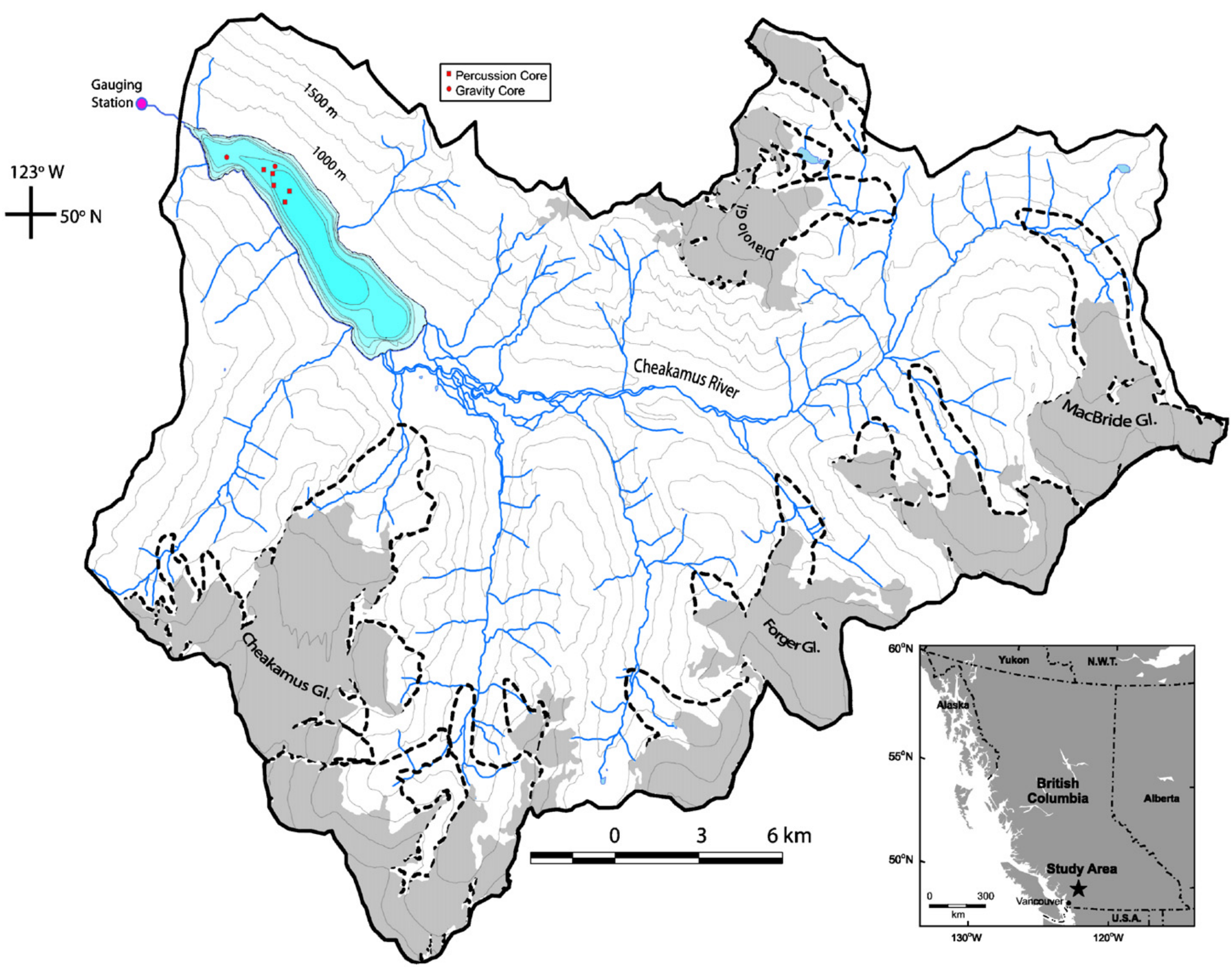

Fig. 1. Location of study area, map of Cheakamus Lake watershed, and lake bathymetry. Dotted lines denote maximum extent of Little Ice Age glaciers. Isobaths less than 40 m are omitted for clarity.

Ice Age when ice cover in the watershed was 30% (Fig. 1; Mathews, 1951; Koch et al., 2004). Most Little Ice Age moraines in Garibaldi Park were constructed between AD 1700 and 1850; the outermost moraines of at least two of the glaciers date to about AD 1700 (Koch et al., 2004, 2007).

Annual precipitation decreases from 1700 mm yr^{-1} near Mt. Garibaldi to approximately 700 mm yr^{-1} at Birkenhead Lake, north of Garibaldi Park (Fig. 1). Almost 75% of the precipitation falls as snow between October and March (Koch et al., 2004).

The Water Survey of Canada maintains a gauging station on Cheakamus River about 3 km below the lake outlet. Flow data are available for the period 1923–1948 and after 1983. Annual runoff from the catchment is dominated by high nival flows during early summer, supplemented in late summer by glacier runoff. Rainstorms during late summer and autumn, which are common in the southern Coast Mountains (Melone, 1985), deliver large amounts of sediment to lakes in the region (Desloges and Gilbert, 1994; Menounos et al., 2005; Gilbert et al., 2006; Schiefer et al., 2006).

Contemporary sediment sources include Little Ice Age moraines, unvegetated sediments in glacier forefields, the glaciers themselves, and steep unstable slopes, mainly in the headwaters of Cheakamus River (Fig. 1). Sediment derived from these sources is temporarily stored in bars along the lower, braided reaches of Cheakamus River. The absence of river terraces and the low gradient of the floodplain upstream from the lake suggest the river prograded its floodplain at least 2 km into the lake during the Holocene.

3. Methods

We recovered five percussion cores (2.0–4.5 m) and two gravity cores (0.25–0.35 m) from Cheakamus Lake in 2000 and 2001 (Fig. 1), and conducted a 3.5-kHz acoustic survey of the lake in 2002. Equipment failure prevented us from completing the 3.5-kHZ survey, but we were able to image 10–20 m of acoustically stratified sediments in the deepest, central portion of the lake basin.

We cut the percussion cores into 1-m sections for helicopter transport. We split and photographed the cores, and collected sediment samples with a modified plastic syringe of known volume. We measured the water content, sediment density, and organic matter content at a 1-cm interval in core 02-Cheak(B) and a 2-cm interval in core 02-Cheak(E).

The loss-on-ignition (LOI) method was used to estimate organic matter content (Dean, 1974). Representative samples were treated with 35% H_2O_2 and dispersed in a sodium metaphosphate solution prior to analysis with a Malvern particle size analyzer. A spruce (*Picea* sp.) needle recovered from one of the percussion cores (01-Cheak(E)) was radiocarbon-dated at IsoTrace Laboratory. The radiocarbon age was converted to a calendric age with the calibration program CALIB 5.0.2 (Stuiver et al., 2005).

Polished slabs and thin sections were prepared from sediments impregnated with low viscosity resin. Lamina thickness ($\pm$0.05 mm) was measured under a dissecting microscope (Lamoureux, 2001). We also measured and characterized laminae from images of wet and partially dried sediment cores (Gilbert, 1975). Minor to moderate deformation induced by coring (coning) required that we measure lamina thickness along the central undisturbed portion of the sediment cores. Lamina thickness in the longest core (01-Cheak(E)) could not be measured due to severe coning, but distinctive marker beds and bulk physical properties allowed us to correlate this core with other, less disturbed ones. We assessed varve counting errors by recording the number of missing or false varves observed in the thin sections, polished slabs, and photographs (Lamoureux, 2001).

Using marker varves (Lamoureux, 2001), we combined varve measurements from the percussion and gravity cores to produce a master chronology. Sedimentation rates at the core sites are not statistically different, thus the master chronology is based on average varve thicknesses at all core sites for a given year. Average inter-series Pearson correlation of the individual varve series (r) is 0.87. Prior to AD 1350, the varve chronology is based on a single core; trends in thickness prior to this time are interpreted with caution. The chronology consists of four cores between AD 1350 and 1940 and three to seven cores thereafter.

Core 00-Cheak(A) appears to be missing two varves. We suspect that high-energy underflows originating from small creeks that enter the lake near the coring site eroded these varves. A more common problem is uncertainty about whether two couplets (a typical silt–clay couplet followed by a much thinner couplet) represent 2 yr of sedimentation or 1 yr, with a late summer or autumn inflow event. Examination of several cores and confirmation of clay caps in thin sections and polished slabs helped reduce potential counting errors caused by this process.

4. Results

4.1. Sedimentology of cores

Recovered sediments from Cheakamus Lake consist of rhythmically laminated and bedded, inorganic clayey silt (Fig. 2). The median grain size (D_{50}) is fine silt (7.5 μm). Dry density ranges from 0.75 to 1.35 g cm^{-3} and increases slightly downcore. The downcore change in sediment density is most apparent in cores taken from shallower depths at the southwest end of the lake.

Couplets consist of graded to ungraded silt capped by clay (Fig. 3). Contacts between clay laminae and overlying silt are sharp and flat. Some of the thicker silt layers grade to a clay cap that is proportional in thickness to that of the silt. Otherwise, however, the thickness of clay laminae is not proportional to that of the underlying silt. Silt layers differ in thickness from 0.4 to 50 mm (Fig. 3). Anomalously thick and thin silt layers were easily

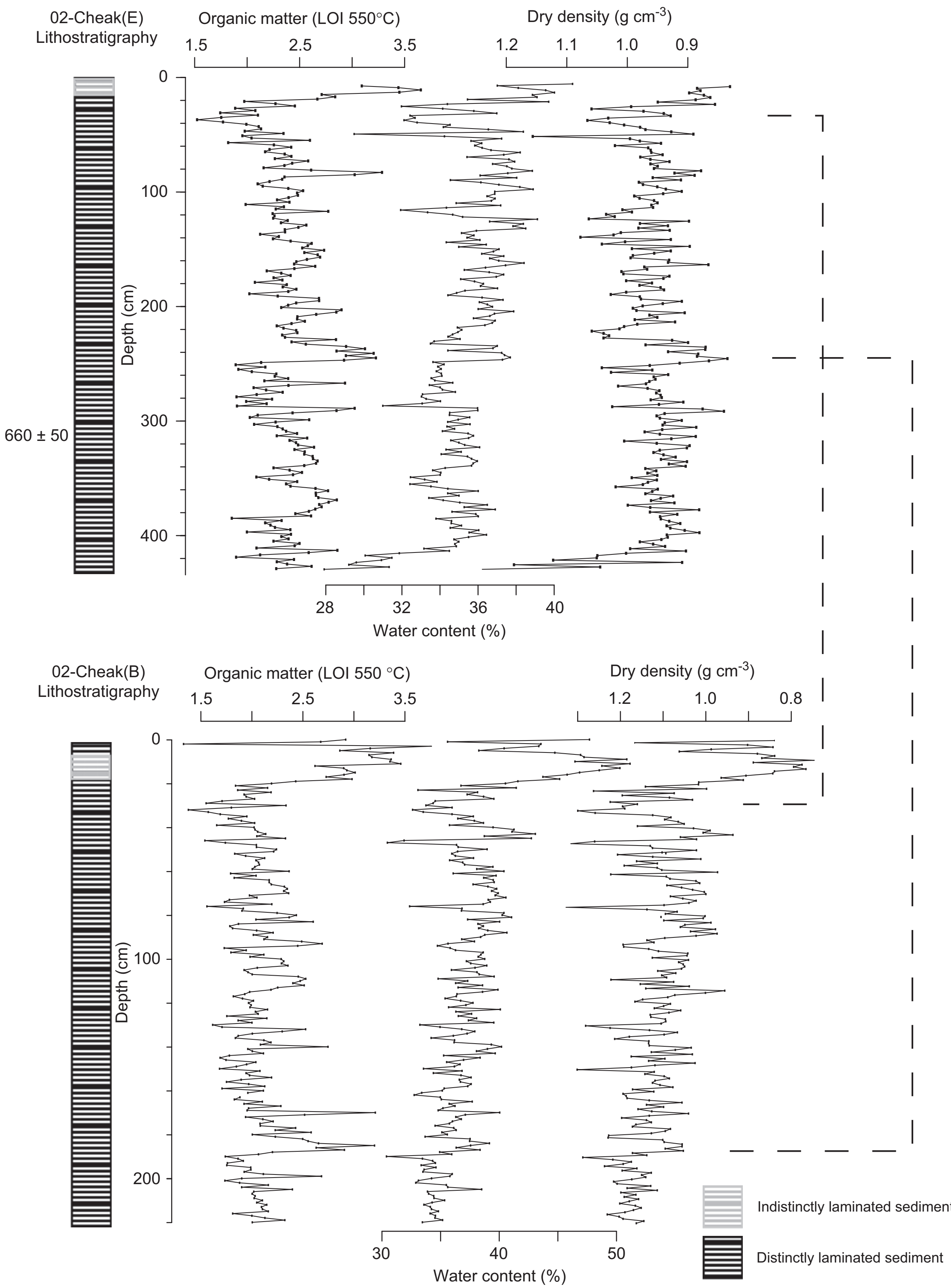

Fig. 2. Bulk physical properties of cores 02-Cheak(B) and 02-Cheak(E). Dashed lines denote proposed correlations.

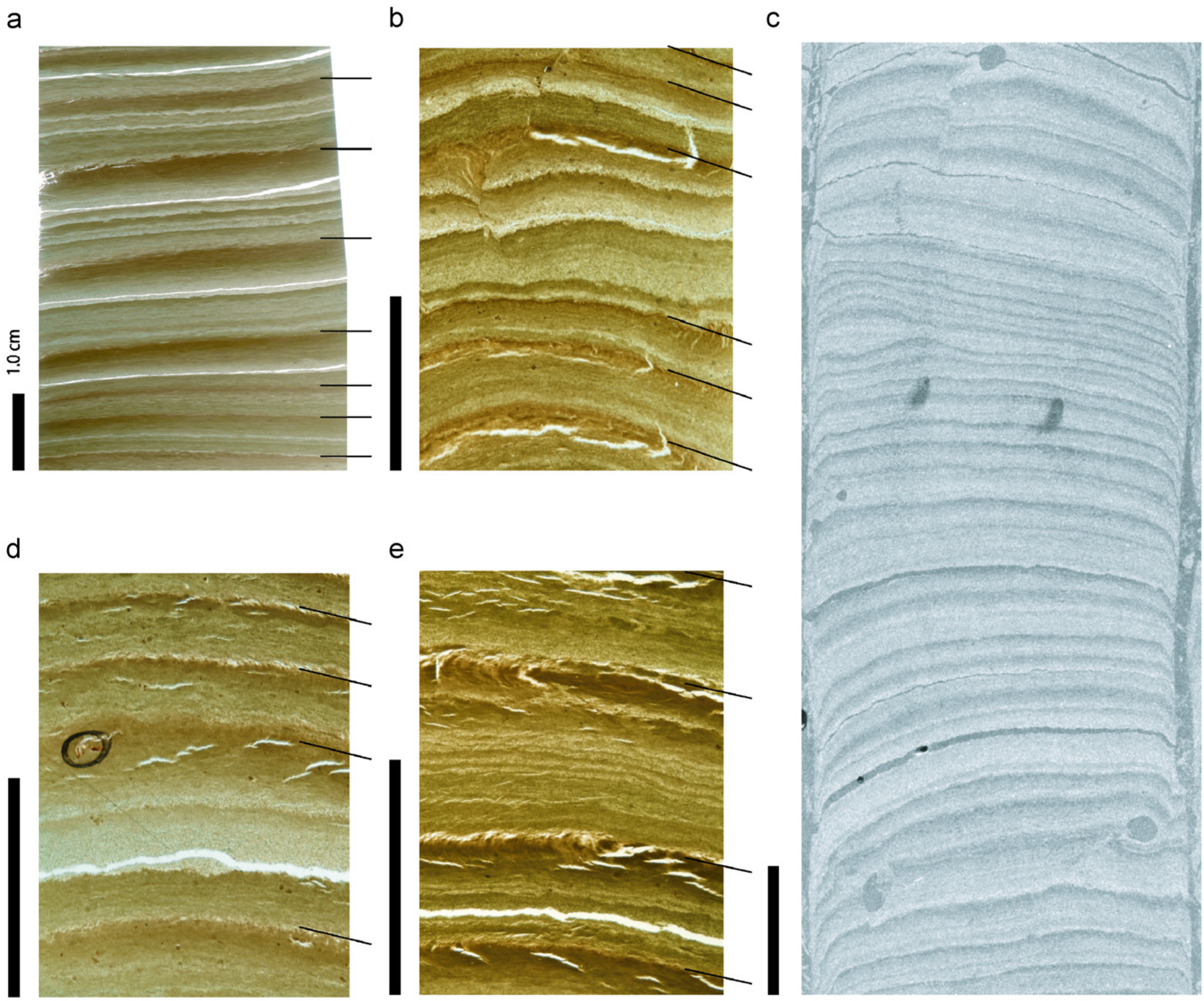

Fig. 3. Representative photo-micrographs of Cheakamus Lake varves (thin black lines denote varve boundaries). All images except part (c) are polished thin sections and are illuminated with transmitted light. (a) Well-preserved sub-laminae in early 20th century varves; (b) three sub-annual laminae; (c) roughly polished slab from core 01-Cheak(A), showing good contrast between silt layers (light) and overlying clay (dark); small dark circles are resin-filled voids; (d) late-season, graded lamina within couplet; the black oval directly above this lamina is a body segment of an unidentified chironomid; (e) micro-laminated varve with at least 15 sub-annual laminae; the thin horizontal cracks are due to freezing during preparation of the sediments for resin impregnation.

correlated from core to core. The spruce needle recovered from core 02-Cheak(E) at 315 cm depth yielded a radiocarbon age of $660 \pm 50\,^{14}$C yr BP (TO-11469); its 95% calibrated age range is AD 1270–1400.

Sediments below 50 cm consist of inorganic, clayey silt (Fig. 2). Sediments between about 20 and 50 cm depth are denser and contain less organic matter than overlying and underlying sediments (Fig. 2). The couplets in this interval are thicker on average and are commonly micro-laminated. The upper 20 cm of sediment are the most organic rich (3.5% LOI), and couplets in this interval are diffuse and moderately bioturbated. Evidence for bioturbation includes fecal pellets and trace fossils.

4.2. Varve chronology

The couplets in the Cheakamus Lake cores are interpreted to be varves. This interpretation is supported by the overlapping calibrated age range of the radiocarbon dated sample (AD 1270–1400) and the varve age (AD 1379 ± 7) at 315 cm depth in core 01-Cheak(E). A correlation between flood magnitude and varve thickness, discussed ahead, also suggests the couplets are varves. Although we do not have the data, our varve interpretation would be strengthened by comparing the number of couplets to the ^{137}Cs or ^{210}Pb activity of the sediments (Lamoureux, 1999; Menounos et al., 2005).

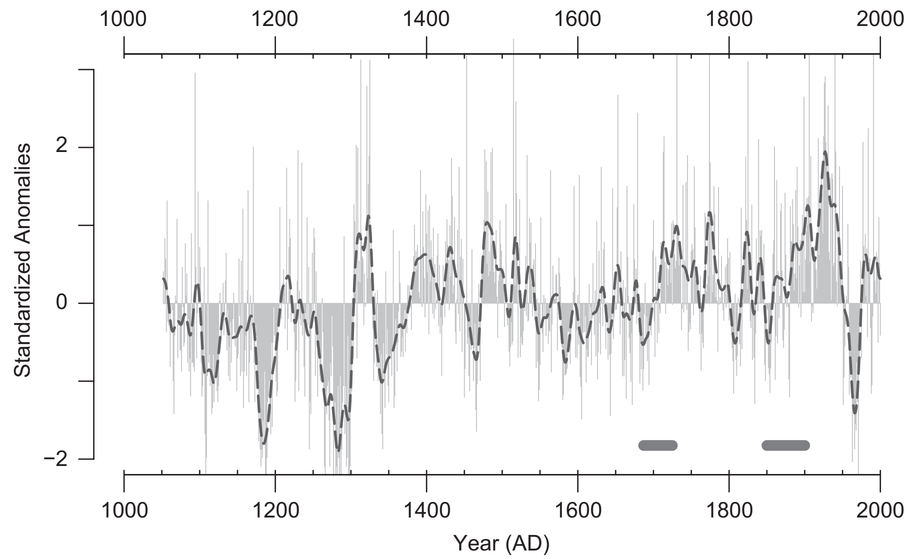

Fig. 4. Varve thickness series based on Cheakamus Lake cores. Varve thickness has been log-transformed to emphasize low frequency variability. Dashed grey line is the decadally smoothed record (31-yr Gaussian-filtered series). The mean inter-series correlation is $r = 0.87$. The number of contributing cores is one from AD 1032 to 1538, four from AD 1350 to 1940, and three to seven thereafter. Thick boxes indicate ages of Little Ice Age moraines in Garibaldi Park (Mathews, 1951; Koch et al., 2007).

The number of false varves (one varve counted as two) is larger than the number of missing varves. False varves may account for errors of 0.6%, whereas missing varves represent only 0.1% of the record. The total uncertainty, taken to be the sum of missing and extra varves, is 0.7%, or approximately one varve per century.

Varve thickness varies at decadal to centennial time scales (Fig. 4). Varves are thicker on average during eight intervals: AD 1090–1110, 1210–1250, 1310–1330, 1390–1450, 1470–1500, 1720–1780, 1860–1900, and 1920–1945. Thinner-than-average varves date to AD 1110–1120, 1170–1200, 1260–1300, 1330–1380, 1450–1470, 1580–1600, 1680–1700, 1800–1815, 1908–1920, and 1950–1980. More broadly, the period AD 1570–1700 was one of below-average sedimentation rates.

4.3. Varve type and inflow variability

We explored the environmental controls on Cheakamus Lake sedimentation by comparing the varve chronology to hydro-climatic time series that may influence the production and transfer of fine sediment within the study area. The time series included in the analysis are regional precipitation and temperature records, glacier mass balance records, snow course data, and Cheakamus streamflow records. Varve thickness is most highly correlated ($r = 0.75$; $n = 41$; $p < 0.001$) to the annual maximum daily flood for a given year (Fig. 5). The correlation is reasonably good, but half of the variance in varve thickness remains unexplained. Micro-statigraphic analysis indicates that many varves contain sub-annual laminae produced by discrete high flows into the lake (Desloges and Gilbert, 1994; Lamoureux, 2000; Schiefer et al., 2006).

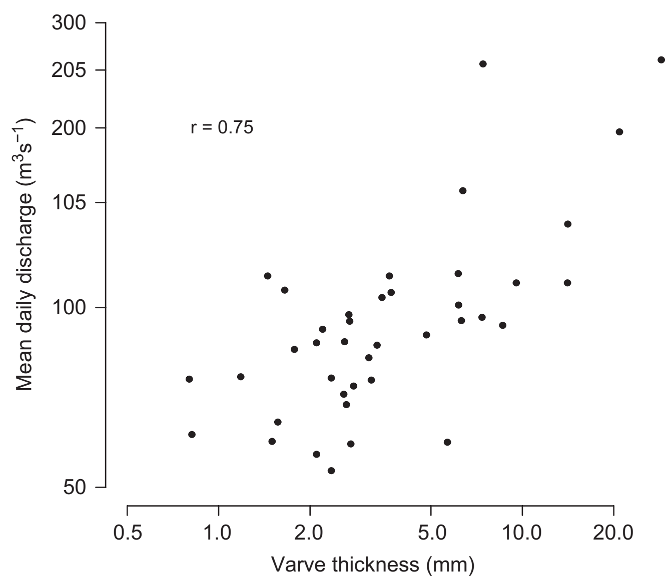

Fig. 5. Relation between annual, maximum, mean daily discharge of Cheakamus River and varve thickness.

We compared the AD 1923–1948 varves to annual hydrographs of Cheakamus River to determine whether the number and thickness of sub-annual laminae are related to the inflow variability of a particular year. Varves deposited after AD 1948 are thin and moderately bioturbated, and thus were not included in the analysis. In general, the agreement between the number and thickness of sub-annual laminae and the number and magnitude of high flow events during a particular year is good (Fig. 6). This correspondence, however, depends on the seasonal timing of the floods and the length of time

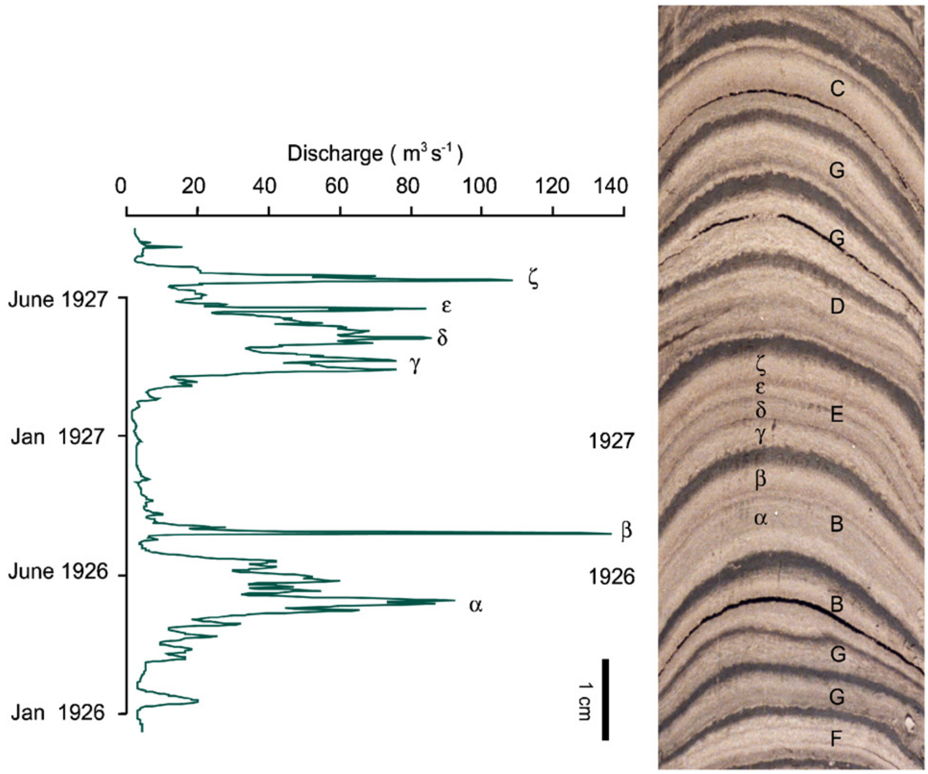

Fig. 6. Comparison of sub-annual events and annual maximum mean daily discharge of Cheakamus River for hydrologic years 1926 and 1927. Letters indicate varve type. Inferred discharge peaks that produced sub-annual laminae are indicated with Greek letters.

separating them (Cockburn and Lamoureux, 2007). For example, early season (January–March) inflow events generally do not produce distinct, sub-annual laminae, and it is difficult to detect sub-annual laminae if high flows were separated by only 1 or 2 weeks.

Other researchers have classified varves into couplets that were formed primarily during early and late-season runoff events (Cockburn and Lamoureux, 2007). The excellent preservation of the Cheakamus Lake varves allowed us to compare the annual hydrographs to the sub-annual stratigraphy. This analysis partitioned the varves into seven major types (Table 1). Inflow conditions associated with the seven varve types are (A) snowmelt flood, (B) autumn flood, (C) mid-season flood, (D) years with two major floods, (E) years with three major floods, (F) years with more than three major floods, and (G) years of substantial glacial runoff. Additionally, some varves (types H and I) contain distinctive, brown, sub-annual laminae or layers of plant detritus, which we interpret to result from sub-aqueous failures of lacustrine sediments (i.e., surge currents generated by sediment slumping along the steep sides of the lake or the delta slope) or from debris flows or snow avalanches along the north side of the lake. We were unable to classify 17 varves because the laminae were diffuse, too thin, or bioturbated. We randomly assigned a type to these varves to develop a continuous time series.

Varves attributed to glacial runoff (type G) and autumn floods (type B) are most common; types H and I varves are rare (Fig. 7). Type B and C varves are thicker on average than other types and include significant positive outliers (Fig. 7). Varve type is not random; some types show inter-decadal to decadal clustering (Fig. 8). Clustering is most pronounced for type G varves at ca AD 1440–1460, 1550–1580, 1770–1800, and 1920–1930.

Table 1
Varve types and their interpretation

Varve type	Description	Interpretation
A	Lower graded lamina in varve	Early season runoff event
B	Upper graded lamina in varve	Late season runoff event
C	Graded lamina in middle of varve	Mid-season runoff event
D	Two-graded laminae	Two major inflow events
E	Three-graded laminae	Three major inflow events
F	>Three-graded laminae	>Three major inflow events
G	Microlaminated (>50% couplet thickness)	Sustained glacier runoff
H	Brown-graded lamina in varve	Turbidite
I	Ungraded organic debris in varve	Snow avalanche (?)

4.4. Markov analysis of varve type

We conducted a Markov analysis to assess whether varve types occur randomly through time (Davis, 2002; Mächler and Bühlmann, 2004). In this analysis, varve types are assumed to be mutually exclusive and their ordering through time can be tested for serial dependence. The series is compared to the expected transition frequencies between varve types, derived from the relative frequencies of each type. The expected transition frequencies are determined by multiplying the transpose of the observed marginal probability vector by the total number of observed types (Table 2). We evaluated the similarity between expected and observed transition frequencies with a Chi-squared test.

The observed frequencies in varve types (Table 2) differ significantly from expected frequencies for a random distribution of varves through time ($\chi^2 = 153$; d.f. $= 64$; $p < 2.6\,e^{-9}$). This result suggests that varve type displays first-order Markovian characteristics; in other words varve type at t_0 depends on varve type at t_1. Noteworthy transitions that occur more frequently than expected (+) include G→G (+42) and E→D (+12). Transitions that occur less frequently than expected (−) include A→G (−14) and G→D (−16). Variable-length, Markov chain analysis reveals that the most frequent second and third-order chains are G→B ($n = 21$), G→E ($n = 24$), G→G ($n = 33$), G→G→D ($n = 15$), and G→G→G ($n = 60$).

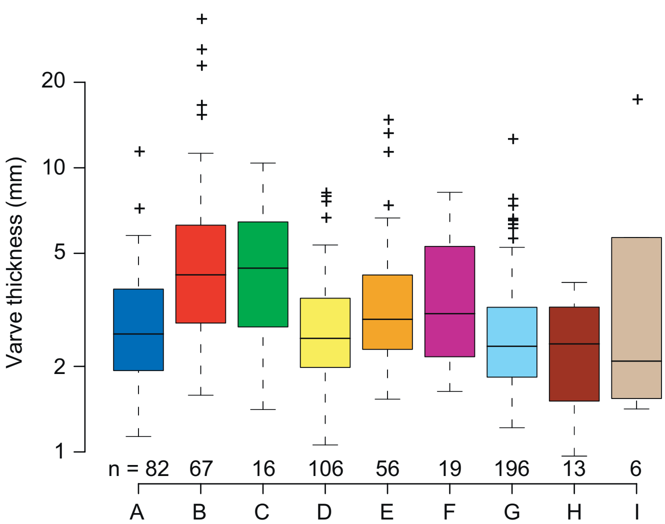

Fig. 7. Box-and-whisker plots of varve type. Box boundaries denote 25% and 75% quantiles, and whiskers delimit 5% and 95% quantiles.

4.5. Relation between air temperature and varve thickness

Varve thickness in nearby Green Lake (Fig. 1) is positively correlated with regional air temperature anomalies during the March–October period (Menounos, 2006).

Table 2
Observed transition frequencies

From	To: A	B	C	D	E	F	G	H	I	Row total	[M][a]
A	18	9	1	16	14	3	14	5	1	81	0.145
B	11	7	0	12	9	2	24	1	1	67	0.120
C	2	1	3	3	3	0	4	0	0	16	0.029
D	21	14	5	25	10	5	24	0	2	106	0.189
E	5	9	0	23	4	3	11	1	0	56	0.100
F	5	3	1	3	1	3	2	0	1	19	0.034
G	18	22	5	21	12	2	111	4	1	196	0.350
H	1	0	1	2	2	1	5	1	0	13	0.023
I	1	1	0	1	1	0	1	1	0	6	0.011
Column totals	82	66	16	106	56	19	196	13	6	560	

[a]The marginal probability vector [**M**] is obtained by dividing the row total by the grand total (560). The expected transition frequencies for a given row are the product of the row total and the transpose of [**M**].

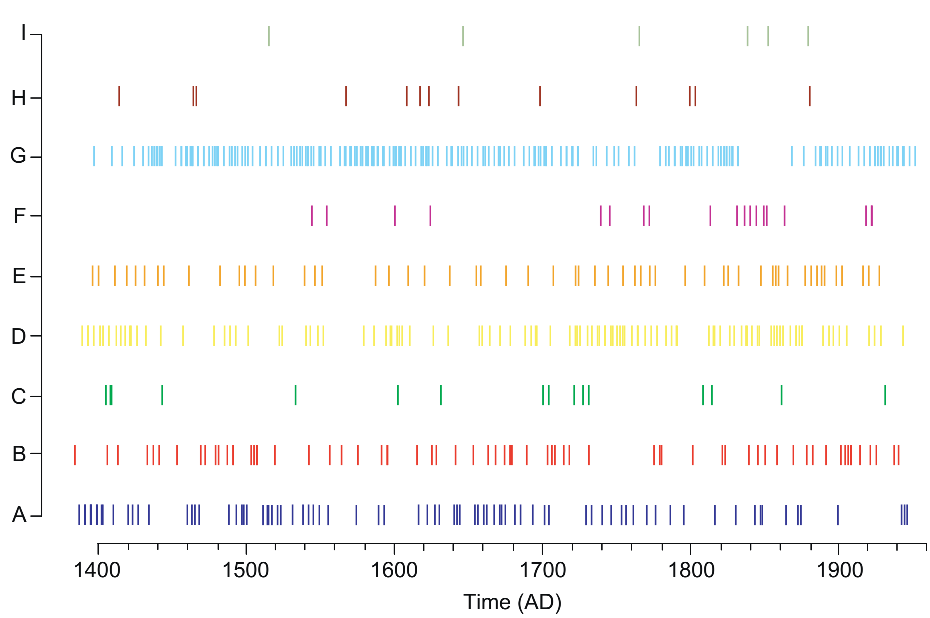

Fig. 8. Varve type versus time. Letters refer to varve type summarized in Table 1.

Although no significant relation exists between varve thickness in Cheakamus Lake and air temperature during the 20th century (Menounos et al., 2005), a moderate correlation exists between Cheakamus Lake varve thickness and reconstructed Northern Hemisphere temperatures for the period AD 1402–1960 (Table 3). The temperature reconstruction is based on the leading principal component extracted from nine regional and hemispheric temperature series; the relation is most apparent in centennial-smoothed records (Fig. 9). The first principal component explains 51% of the variance common to the temperature reconstructions. Negative anomalies in the centennial-smoothed records are apparent in the varve and temperature records in the mid-1400s, 1600s, and early 1800s (Fig. 9). The highest positive anomalies in both records are in the early 20th century. Surprisingly, the Cheakamus Lake sedimentation series leads the air temperature reconstruction by about 10–20 yr (Table 3; Fig. 9).

Table 3
Pearson correlation coefficients of varve thickness and the first principal component extracted from nine air temperature reconstructions for the period AD 1402–1960

Period of correlation (AD)	Pearson correlation	Cheakamus leads AT (yr)
1402–1960	0.34	9
1861–1960	0.40	20
1861–1402	0.25	4
1761–1402	0.24	2
1661–1402	0.29	1
1551–1402	0.22	1

Note: All correlation coefficients are significant ($p < 0.001$) and are based on unsmoothed records. Temperature reconstructions are based on published work (Overpeck et al., 1997; Briffa et al., 1998, 2001; Jones et al., 1998; Mann et al., 1998; Esper et al., 2002; Luckman and Wilson, 2004; Moberg et al., 2005; Rutherford et al., 2005).

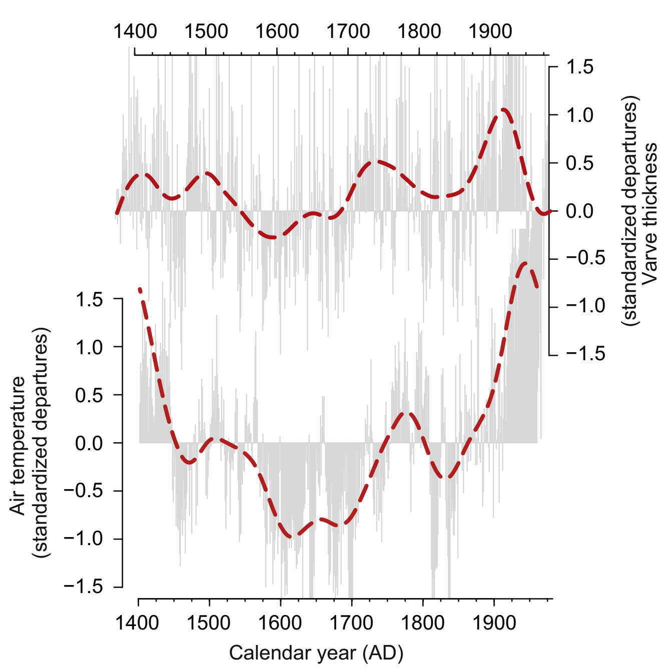

Fig. 9. Standardized anomalies of Cheakamus Lake varve thickness and the first principal component of regional and Northern Hemisphere temperature reconstructions (Table 3). The red, dashed lines are centennially smoothed series (101-yr Gaussian filter). Anomalies < -1.5 and > 1.5 are omitted to emphasize the low-frequency pattern in the data.

5. Discussion

5.1. Sediment sources and delivery processes

Cheakamus Lake is a typical, western Canadian, proglacial, montane lake (Gilbert, 1975; Smith, 1978; Desloges and Gilbert, 1994). Glaciers, high relief, and a maritime climate ensure that abundant clastic sediment is delivered to the lake each year. The simple geometry of the basin and inferred high sediment load of Cheakamus River probably allow sediment to reach the coring sites by turbidity currents during extreme runoff events and by interflows and overflows during late summer and early autumn (Gilbert, 1975; Best et al., 2005).

The maritime setting of the watershed allows significant quantities of sediment to reach the lake during autumn floods (Desloges and Gilbert, 1994; Menounos et al., 2005; Gilbert et al., 2006; Schiefer et al., 2006). A positive relation between varve thickness and autumn flooding is confirmed from the hydrograph records for the periods AD 1923–1948 and after AD 1983. It is also supported by documentary evidence prior to the first streamflow records. The 1906 varve, for example, consists of two, normally graded silt laminae. The upper lamina has a clay cap and conformably overlies the lower lamina, which lacks a clay cap. This stratigraphy is interpreted to record two closely spaced floods within a single year. Newspaper records from Vancouver describe regional damage and fatalities caused by two intense rainstorms in September of 1906 (Menounos et al., 2005).

5.2. Runoff variability and varve thickness

Markov analysis reveals that varve type does not occur randomly through time. Micro-laminated varves or varves that record two and three major inflow events preferentially follow one another. The thickest varves commonly contain late season laminae (type B) and tend to follow varves that are micro-laminated (type G). This correspondence may arise from persistence in climatic conditions, in which there are clusters of years with multiple inflow events and autumn flooding. The coincidence may also be partly explained by changes in sediment availability. For example, significant fine-grained sediment is stored in Coast Mountain rivers if annual flows decline steadily through autumn and especially during years of substantial glacier runoff (Richards and Moore, 2002). The stored fine-grained sediment may be mobilized the next year if high flows occur during autumn. However, such changes in sediment availability probably do not account for deposition of micro-laminated layers immediately before early-season events, because varves interpreted to record early-season floods show no correspondence to varves deposited during the preceding year.

The independence of type B varves suggests that they record unique meteorological conditions that are not common to any particular climate regime. Similarly, varves interpreted to form predominantly during early season floods (type A) appear to be randomly distributed through time. These findings are generally in accord with the stochastic nature of flooding in the southern Coast Mountains (Melone, 1985).

In contrast, type G varves are highly serially correlated and are dominant during specific periods (Fig. 8). These periods are interpreted to be times of heightened glacier runoff to the lake basin. Years in which monitored glaciers in western North America have lost mass are warmer and drier than average (Hodge et al., 1998; Bitz and Battisti, 1999). Some of the intervals of type-G varves coincide with times of warmer-than-average reconstructed air temperatures for the Northern Hemisphere and North America (Fig. 9). Warm temperatures and sustained glacier runoff promote the formation of micro-laminated varves by delivering a quasi-continuous supply of fine-grained sediment to Cheakamus Lake during summer; the sediment probably reaches the coring sites by interflows and overflows.

5.3. Relation between glacier extent and sedimentation rates

Glaciers are known to increase sediment yield in mountain watersheds (Harbor and Warburton, 1993; Hallet et al., 1996). One would expect a positive relation between percent ice cover and sediment yield, because more extensive ice increases the total area of sub-glacial erosion (Hallet et al., 1996). However, the relation between ice cover and lake sedimentation is not a simple one and is governed by other factors, including climate regime, changes in sediment storage, and lags between sediment production and delivery to lakes. Leonard (1997), for example, reported a complex relation between glacierized area and sedimentation in Hector Lake, Alberta. Sedimentation rates were high not only at times when glaciers were extensive, but also during periods of rapid glacier advance and retreat.

Particularly thick varves in Cheakamus Lake date to AD 1300, 1490, 1710, 1770, and from AD 1900 to 1940. Some of these intervals coincide with periods when glaciers achieved their maximum downvalley extents during the Little Ice Age (Fig. 4) and with periods of rapid glacier retreat. Most glaciers reached their maximum Little Ice Age positions in Garibaldi Park at about AD 1700 and 1850 (Mathews, 1951; Koch et al., 2004). In the adjacent Green Lake watershed, Overlord Glacier constructed its second outermost moraine in AD 1702, based on a tree damaged by the advance (Osborn et al., 2007). Warren Glacier, 12 km southwest of Cheakamus Lake, was at its Little Ice Age limit in AD 1705 (Koch et al., 2007). Glaciers within and adjacent to the Cheakamus Lake watershed retreated in the 20th century and at particularly high rates between AD 1930 and 1945 (Ricker, 1978; Menounos et al., 2005). The highest sedimentation rates of the past 700 yrs date to this period (Fig. 4), and the highest decadally averaged sediment yields in the nearby Green Lake watershed also occurred at this time (Menounos et al., 2006). High sedimentation rates in the early 20th century have also been documented for Hector and Bow lakes (Leonard, 1981, 1997). In the Bow Lake example, the highest sedimentation rates of the past 300 yrs occurred during the period AD 1920–1944. The period 1920–1944 was a notably warm and dry period in western Canada (Menounos, 2006), and glaciers, which earlier were near their Little Ice Age limits, retreated quickly. Similarly, the highest sedimentation rates of the 20th century in Icy Bay, Alaska, occurred during periods of rapid glacier retreat (Koppes and Hallet, 2006).

Many glaciers in Garibaldi Park advanced some 200–300 m between AD 1945 and 1980 (Ricker, 1978; Koch, 2006). Regional snowfall was above average, and mean annual temperatures were below average, through most of this period (Menounos et al., 2005). Varves dating to AD 1945–1980 are the thinnest of the past 1000 yrs and moderately bioturbated (Fig. 4). Cooler temperatures probably limited sediment delivery by reducing sub-glacial discharge and melt of debris-rich ice. They may also have shortened the time that proglacial sediment sources were snow-free. Moderate bioturbation is explained by low sedimentation rates and low turbidity levels, both of which enhance reworking of sediment by infauna (Lloyd et al., 1987; Grimm et al., 1996).

Our data suggest that thin varves were deposited at times when glaciers were relatively stable, neither rapidly retreating nor rapidly advancing. It would appear that, at time scales of decades or less, sediment delivery to Cheakamus Lake is poorly predicted by percent glacier cover.

5.4. Lead–lag effects

A consistent lead–lag effect is observed in the varve and temperature records of this study (Fig. 9). This lead–lag effect is present for the unsmoothed records (Table 3) and for different types of smoothing filters (e.g. Gaussian and boxcar) and filter length (31, 51, and 101 yr).

It is unlikely that dating errors explain this lead–lag effect because the relation exists during the period of instrumentation, for which there is a notable correlation between thick varves and flood magnitude (Fig. 5). Dating errors probably have not accumulated downcore because the radiocarbon and varve ages at 315-cm depth are in agreement and the lead–lag effect persists over different intervals of time (Table 3).

One explanation of this lead–lag relation is that it is caused by changes in sediment availability. Years of persistently cooler-than-average climate would initially reduce glacier runoff, producing thin varves. Sedimentation rates might increase once these cooler conditions forced glaciers to advance. Consequently, the lead relation for sedimentation minima may relate to the average response time of the glaciers in the Cheakamus Lake watershed. Response times can be approximated by dividing the average thickness of a glacier by the annual ablation rate at the terminus (Jóhannesson et al., 1989). Based on the estimated thicknesses of glaciers in the headwaters of the Cheakamus River watershed (~100 m) and observed ablation rates at nearby glaciers (M. Demuth, unpublished data), response times of 10–20 yr are expected. Sediment exhaustion may account for the peak in Cheakamus Lake sedimentation before the maximum in the temperature record (Fig. 9).

The cumulative departure plot of the unsmoothed, differenced varve and air temperature records (Fig. 10) accords with the non-continuous terrestrial records of glacier fluctuations in Garibaldi Park during the Little Ice Age (Koch et al., 2007). Thick varves not explained by positive air temperatures were deposited from about AD 1600 to 1750 and from AD 1800 to 1850 (Fig. 10). These periods coincide with intervals when glaciers were advancing in Garibaldi Park (Mathews, 1951; Koch et al., 2007) and elsewhere in western Canada (Osborn and Luckman, 1988; Luckman, 2000). Thicker-than-normal varves persist for 20–30 yr after stabilization of outermost Little Ice Age moraines in Garibaldi Park (Fig. 10). Thick varves may relate to more extensive ice cover (Hallet et al., 1996) or perhaps to a short interval of paraglacial sedimentation during glacier recession (Ballantyne, 2002). The only substantial run of negative cumulative departures is after AD 1925 (Fig. 10). This interval coincides with rapid ice retreat in Garibaldi Park and nearby watersheds (Menounos et al., 2005).

5.5. Regional comparisons

The Cheakamus Lake varve record shows some correspondence with those from nearby Green Lake (Menounos, 2006) and lakes in the Canadian Rockies (Leonard, 1981, 1997) (Fig. 11). All lakes contain thick varves deposited in the early 1700s and between AD 1775 and 1800. The thickest varves in Cheakamus, Green, and Bow lakes date to AD 1925–1950. Glaciers in both the southern Coast Mountains and the Canadian Rockies rapidly retreated during the period AD 1925–1950 (Osborn and Luckman, 1988; Luckman, 2000; Menounos et al., 2005).

Thick varves accumulated in Green and Cheakamus Lakes from AD 1875 to 1900, whereas sedimentation in Bow and Hector lakes during this period was lower than average (Fig. 11). The reasons for this difference are unknown but may include dating errors in all the records. Similarly, the cause of the poor correlation between the Cheakamus and Green Lake sediment records prior to AD 1850 is unknown. The poor correlation was unexpected because the records from the two lakes over the past 120 yrs are in accord (Menounos et al., 2005).

6. Broader implications and conclusions

Varved sediments are one of only a few annually resolvable archives of paleoenvironmental information; the other main ones are trees and glacier ice. This study reiterates the complexity of the archive and the difficulties in

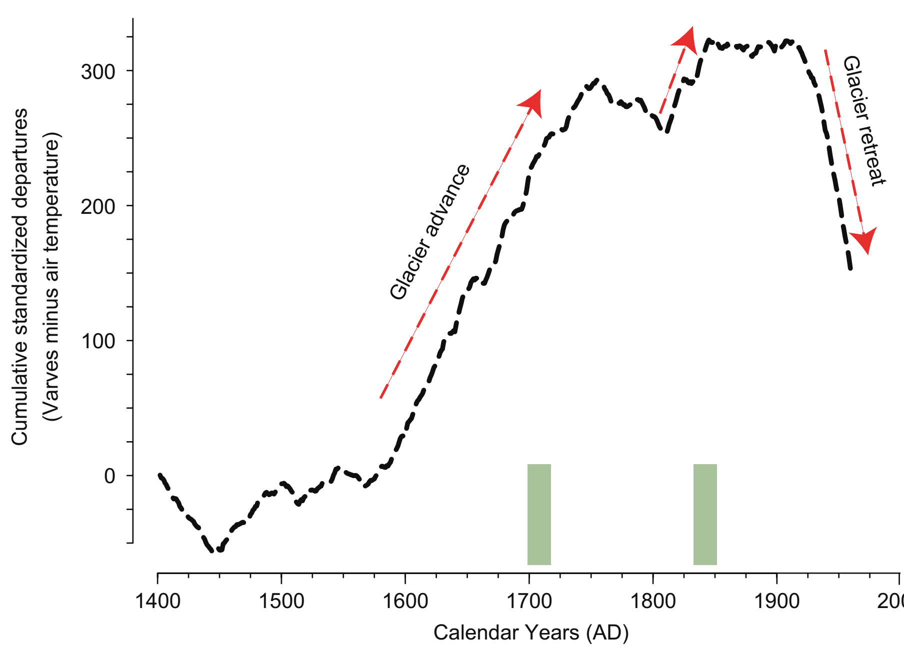

Fig. 10. Cumulative standardized departures of differenced Cheakamus varve and temperature series. Temperature series are those reported in Table 3. Ages of dated Little Ice Age moraines in Garibaldi Park are indicated by green horizontal bars.

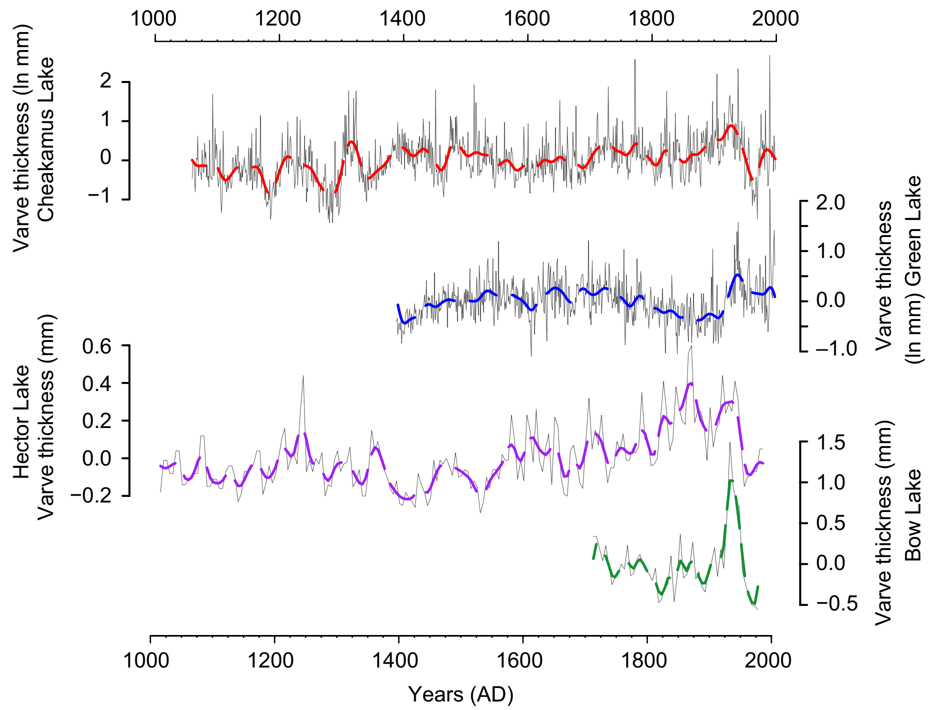

Fig. 11. Standardized anomalies of varve thickness time series for Cheakamus, Green, Hector, and Bow lakes. Hector and Bow lake data are, respectively, 5- and 10-yr averages. Thick dashed lines are smoothed records (30-yr Gaussian filter).

defining the cascade of processes that produce each annual layer in a varve sequence (Hodder et al., 2007). Couplet thickness is an important paleoenvironmental parameter in varve studies, but its relation to environmental controls in proglacial catchments is complex. Correlations between these controls and varve thickness are likely to be, at best, moderate and dependent on the time scale of analysis. At event to inter-annual time scales, valuable paleoenvironmental information can be extracted from varve sequences by documenting the internal stratigraphy and sedimentology of couplets, and by examining varves in relation to contemporaneous hydro-meteorological data within the watershed or surrounding area. As shown in this study, the temporal sequence of different types of varves can also shed light on the processes that control their deposition, namely differences in the magnitude and timing of inflow events to a lake basin. At multi-decadal to century time scales, environmental factors that control the production and delivery of clastic sediments to proglacial lake basins become important. In the Cheakamus Lake catchment, this long-term control includes air temperature and its influence on glacier fluctuations. At all time scales, geomorphic factors such as glacier response time, mass wasting, and sediment transfer and storage between glaciers and the lake confound the relation between lake sedimentation and hydro-climatic events.

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